CHAPTER 4

SOLID-STATE POWER SUPPLIES

LEARNING OBJECTIVES

Upon completion of this chapter you will be able to:

1. Identify the various sections of a power supply.
2. State the purpose of each section of a power supply.
3. Describe the operation of the power supply from both a whole unit standpoint and from a subunit standpoint.
4. Describe the purpose of the various types of rectifier circuits used in power supplies.
5. Describe the purpose of the various types of filter circuits used in power supplies.
6. Describe the operation of the various voltage and current regulators in a power supply.
7. Describe the operation of the various types of voltage multipliers.
8. Trace the flow of ac and dc in a power supply, from the ac input to the dc output on a schematic diagram.
9. Identify faulty components through visual checks.
10. Identify problems within specific areas of a power supply by using a logical isolation method of troubleshooting.
11. Apply safety precautions when working with electronic power supplies.

In today's Navy all electronic equipment, both ashore and on board ship, requires a power supply. The discovery of the silicon diode and other solid-state components made possible the reduction in size and the increase in reliability of electronic equipment. This is especially important on board ship where space and accessibility to spare parts are a major concern.

In this chapter, you will read about the individual sections of the power supply, their components, and the purpose of each within the power supply.

THE BASIC POWER SUPPLY

View A of figure 4-1 shows the block diagram of a basic power supply. Most power supplies are made up of four basic sections: a TRANSFORMER, a RECTIFIER, a FILTER, and a REGULATOR.

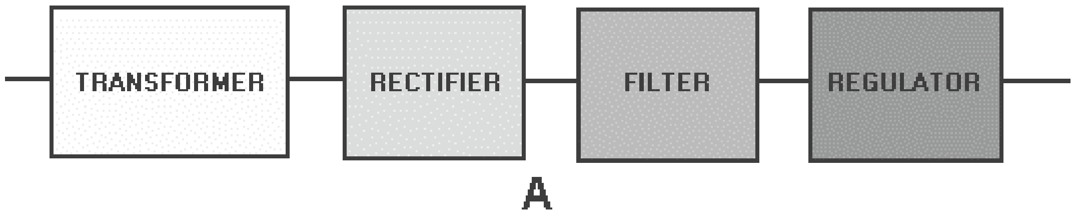


Figure 4-1A.—Block diagram of a basic power supply.

As illustrated in view B of figure 4-1, the first section is the TRANSFORMER. The transformer steps up or steps down the input line voltage and isolates the power supply from the power line. The RECTIFIER section converts the alternating current input signal to a pulsating direct current. However, as you proceed in this chapter you will learn that pulsating dc is not desirable. For this reason a FILTER section is used to convert pulsating dc to a purer, more desirable form of dc voltage.

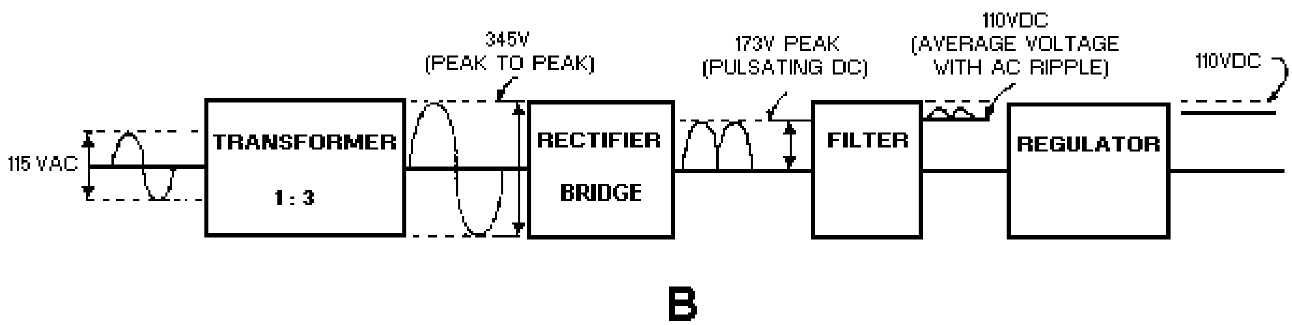


Figure 4-1B.—Block diagram of a basic power supply.

The final section, the REGULATOR, does just what the name implies. It maintains the output of the power supply at a constant level in spite of large changes in load current or input line voltages.

Now that you know what each section does, let's trace an ac signal through the power supply. At this point you need to see how this signal is altered within each section of the power supply. Later on in the chapter you will see how these changes take place. In view B of figure 4-1, an input signal of 115 volts ac is applied to the primary of the transformer. The transformer is a step-up transformer with a turns ratio of 1:3. You can calculate the output for this transformer by multiplying the input voltage by the ratio of turns in the primary to the ratio of turns in the secondary; therefore, 115 volts ac $\times$ 3 = 345 volts ac (peak-to-peak) at the output. Because each diode in the rectifier section conducts for 180 degrees of the 360-degree input, the output of the rectifier will be one-half, or approximately 173 volts of pulsating dc. The filter section, a network of resistors, capacitors, or inductors, controls the rise and fall time of the varying signal; consequently, the signal remains at a more constant dc level. You will see the filter process more clearly in the discussion of the actual filter circuits. The output of the filter is a signal of 110 volts dc, with ac ripple riding on the dc. The reason for the lower voltage (average voltage) will be explained later in this chapter. The regulator maintains its output at a constant 110-volt dc level, which is used by the electronic equipment (more commonly called the load).

Q1. What are the four basic sections of a power supply?

Q2. What is the purpose of the rectifier section?

Q3. What is the purpose of the filter section?

Q4. What is the purpose of the regulator section?

THE POWER TRANSFORMER

In some cases a power supply may not use a transformer; therefore, the power supply would be connected directly to the source line voltage. This type of connection is used primarily because it is economical. However, unless the power supply is completely insulated, it presents a dangerous shock hazard to anyone who comes in contact with it. When a transformer is not being used, the return side of the ac line is connected to the metal chassis. To remove this potential shock hazard and to have the option of stepping up or stepping down the input voltage to the rectifier, a transformer must be used.

View A of figure 4-2 shows the schematic diagram for a STEP-UP transformer; view B shows a STEP-DOWN transformer; and, view C shows a STEP-UP, CENTER-TAPPED transformer. The step-up and step-down transformers were discussed in earlier *NEETS* modules, so only the center-tapped transformer will be mentioned in this chapter. The primary purpose of the center-tapped transformer is to provide two equal voltages to the conventional full-wave rectifier.

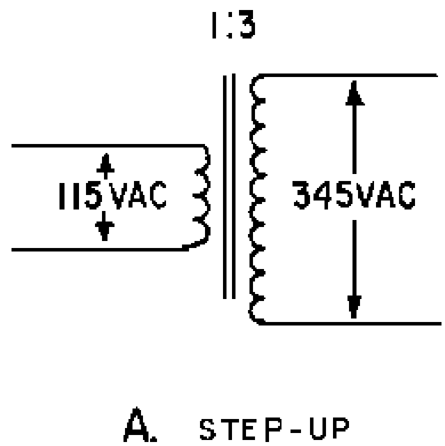


Figure 4-2A.—Common types of transformers. STEP-UP

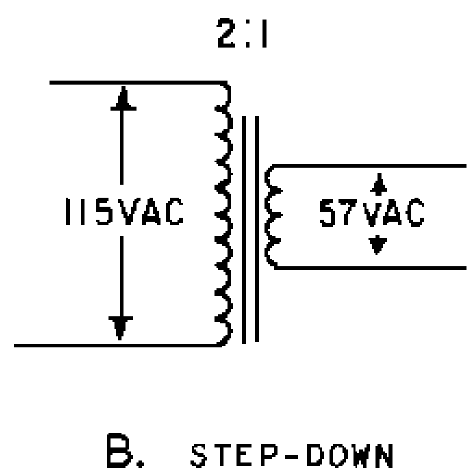


Figure 4-2B.—Common types of transformers. STEP-DOWN

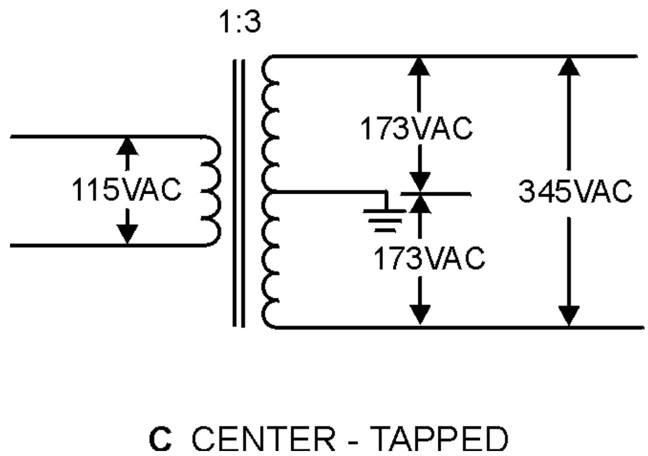


Figure 4-2C.—Common types of transformers. CENTER-TAPPED

THE RECTIFIER

From previous discussions, you should know that rectification is the conversion of an alternating current to a pulsating direct current. Now let's see how the process of RECTIFICATION occurs in both a half-wave and a full-wave rectifier.

The Half-Wave Rectifier

Since a silicon diode will pass current in only one direction, it is ideally suited for converting alternating current (ac) to direct current (dc). When ac voltage is applied to a diode, the diode conducts ONLY ON THE POSITIVE ALTERNATION OF VOLTAGE; that is, when the anode of the diode is positive with respect to the cathode. This simplest type of rectifier is the half-wave rectifier. As shown in view A of figure 4-3, the half-wave rectifier uses only one diode. During the positive alternation of input voltage, the sine wave applied to the diode makes the anode positive with respect to the cathode. The diode then conducts, and current (I) flows from the negative supply lead (the secondary of the transformer), through the milliammeter, through the diode, and to the positive supply lead. As indicated by the shaded area of the output waveform in view B, this current exists during the entire period of time that the anode is positive with respect to the cathode (in other words, for the first 180 degrees of the input sine wave).

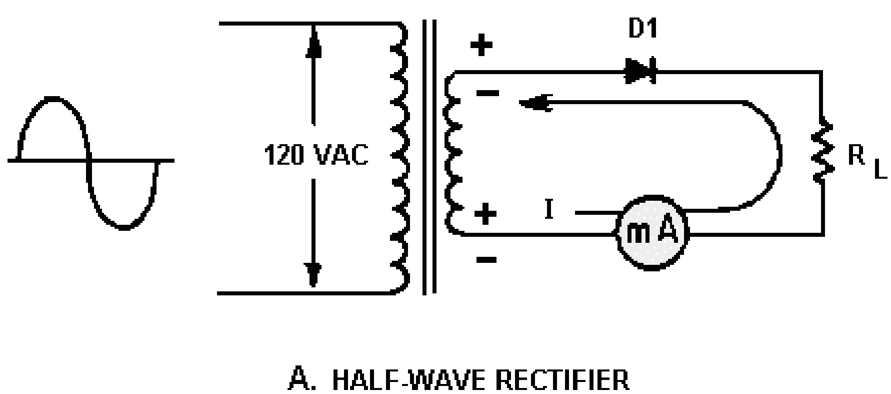


Figure 4-3A.—Simple half-wave rectifier. HALF-WAVE RECTIFIER

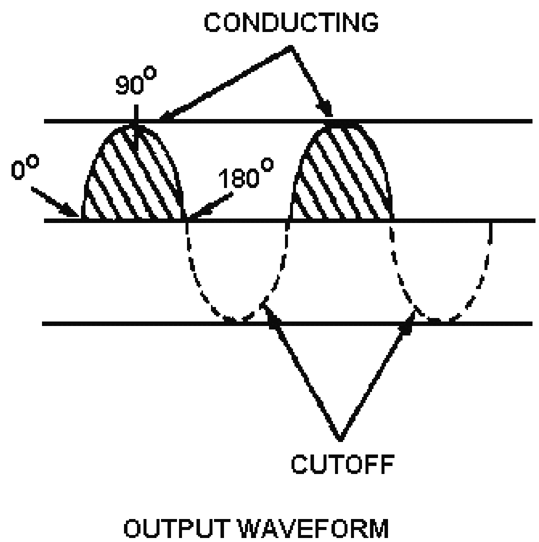


Figure 4-3B.—Simple half-wave rectifier. OUTPUT WAVEFORM

During the negative alternation of input voltage (dotted polarity signs), the anode is driven negative and the diode cannot conduct. When conditions such as these exist, the diode is in cutoff and remains in cutoff for 180 degrees, during which time no current flows in the circuit. The circuit current therefore has the appearance of a series of positive pulses, as illustrated by the shaded areas on the waveform in view B. Notice that although the current is in the form of pulses, the current always flows in the same direction. Current that flows in pulses in the same direction is called PULSATING DC. The diode has thus RECTIFIED the ac input voltage.

Rms, Peak, and Average Values

View A of figure 4-4 is a comparison of the rms, peak, and average values of the types of waveforms associated with the half-wave rectifier. Ac voltages are normally specified in terms of their rms values. Thus, when a 115-volt ac power source is mentioned in this chapter, it is specifying the rms value of 115 volts ac. In terms of peak values,

$E_{rms} = E_{peak} \times .707$

The peak value is always higher than the rms value. In fact,

$E_{peak} = E_{rms} \times 1.414$

therefore, if the rms value is 115 volts ac, then the peak value must be:

$E_{peak} = E_{rms} \times 1.414$

$E_{peak} = 115 \text{ volts ac} \times 1.414$

$E_{peak} = 162.6 \text{ volts}$

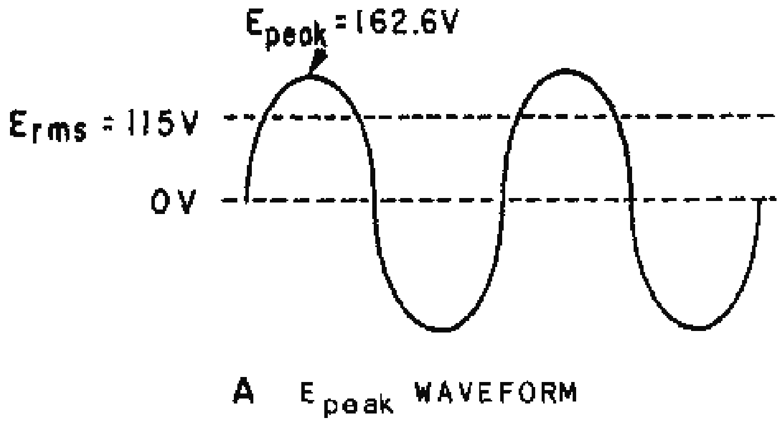


Figure 4-4A.—Comparison of E_{peak} to E_{avg} in a half-wave rectifier. E_{peak} WAVEFORM.

The average value of a sine wave is 0 volts. View B of figure 4-4 shows how the average voltage changes when the negative portion of the sine wave is clipped off. Since the wave form swings positive but never negative (past the "zero-volt" reference line), the average voltage is positive. The average voltage (E_{avg}) is determined by the equation:

Where: $E_{avg} = E_{peak} \times .318$

Thus: $E_{avg} = 162.6 \times .318$

$E_{avg} = 51.7$ volts

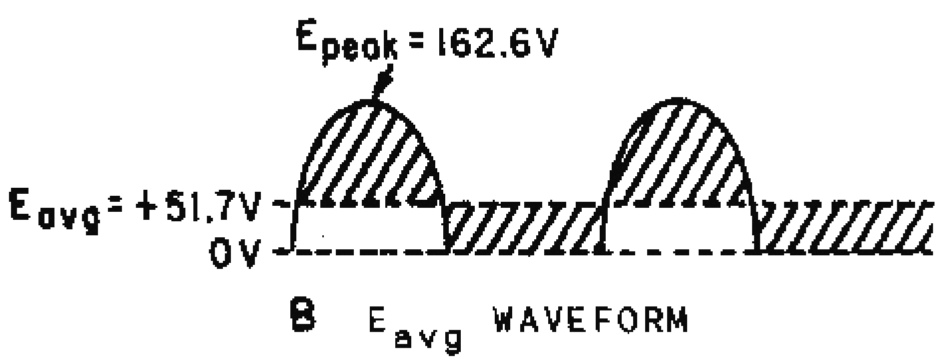


Figure 4-4B.—Comparison of E_{peak} to E_{avg} in a half-wave rectifier. E_{peak} WAVEFORM

Ripple Frequency

The half-wave rectifier gets its name from the fact that it conducts during only half the input cycle. Its output is a series of pulses with a frequency that is the same as the input frequency. Thus when operated from a 60-hertz line, the frequency of the pulses is 60 hertz. This is called RIPPLE FREQUENCY.

Q5. What is the name of the simplest type of rectifier which uses one diode?

Q6. If the output of a half-wave rectifier is 50-volts peak, what is the average voltage?

Q7. In addition to stepping up or stepping down the input line voltage, what additional purpose does the transformer serve?

The Conventional Full-Wave Rectifier

A full-wave rectifier is a device that has two or more diodes arranged so that load current flows in the same direction during each half cycle of the ac supply.

A diagram of a simple full-wave rectifier is shown in figure 4-5. The transformer supplies the source voltage for two diode rectifiers, D1 and D2. This power transformer has a center-tapped, high-voltage secondary winding that is divided into two equal parts (W1 and W2). W1 provides the source voltage for D1, and W2 provides the source voltage for D2. The connections to the diodes are arranged so that the diodes conduct on alternate half cycles.

During one alternation of the secondary voltage, the polarities are as shown in view A. The source for D2 is the voltage induced into the lower half of the secondary winding of the transformer (W2). At the specific instant of time shown in the figure, the anode voltage on D2 is negative, and D2 cannot conduct. Throughout the period of time during which the anode of D2 is negative, the anode of D1 is positive. Since the anode of D1 is positive, it conducts, causing current to flow through the load resistor in the direction shown by the arrow.

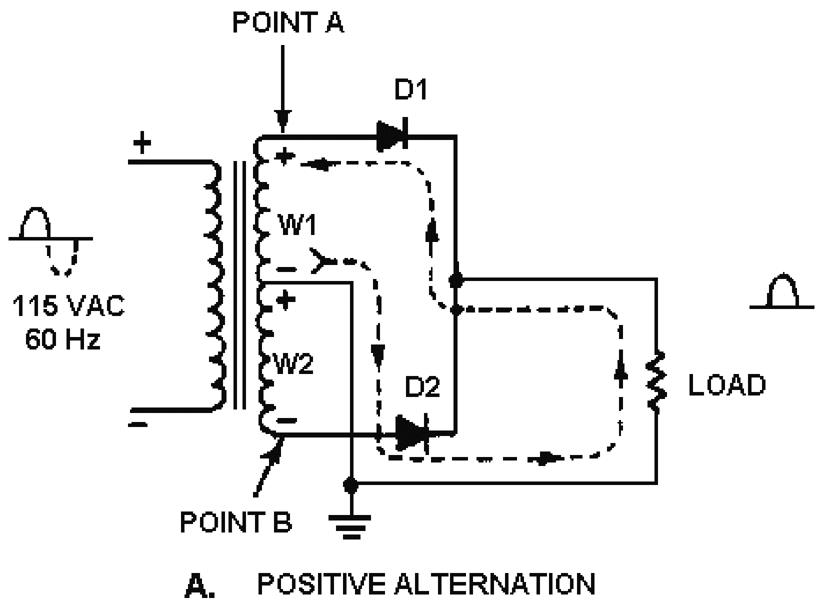


Figure 4-5A.—Full-wave rectifier. POSITIVE ALTERNATION

View B shows the next half cycle of secondary voltage. Now the polarities across W1 and W2 are reversed. During this alternation, the anode of D1 is driven negative and D1 cannot conduct. For the period of time that the anode of D1 is negative, the anode of D2 is positive, permitting D2 to conduct. Notice that the anode current of D2 passes through the load resistor in the same direction as the current of D1 did. In this circuit arrangement, a pulse of load current flows during each alternation of the input cycle. Since both alternations of the input voltage cycle are used, the circuit is called a FULL-WAVE RECTIFIER.

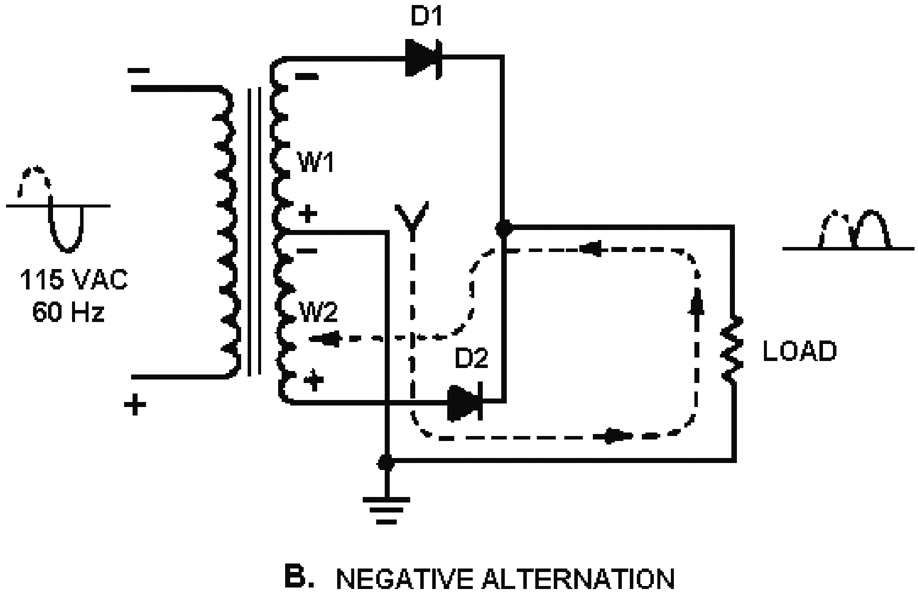


Figure 4-5B.—Full-wave rectifier. NEGATIVE ALTERNATION

Now that you have a basic understanding of how a full-wave rectifier works, let's cover in detail a practical full-wave rectifier and its waveforms.

A Practical Full-Wave Rectifier

A practical full-wave rectifier circuit is shown in view A of figure 4-6. It uses two diodes (D1 and D2) and a center-tapped transformer (T1). When the center tap is grounded, the voltages at the opposite ends of the secondary windings are 180 degrees out of phase with each other. Thus, when the voltage at point A is positive with respect to ground, the voltage at point B is negative with respect to ground. Let's examine the operation of the circuit during one complete cycle.

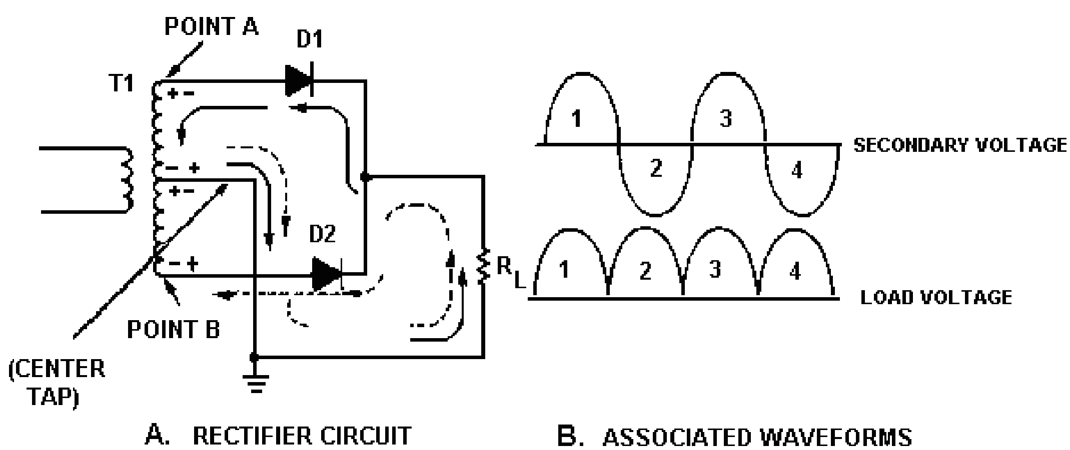


Figure 4-6.—Practical full-wave rectifier.

During the first half cycle (indicated by the solid arrows), the anode of D1 is positive with respect to ground and the anode of D2 is negative. As shown, current flows from ground (center tap), up through the load resistor (R_L), through diode D1 to point A. In the transformer, current flows from point A, through the upper winding, and back to ground (center tap). When D1 conducts, it acts like a closed switch so that the positive half cycle is felt across the load (R_L).

During the second half cycle (indicated by the dotted lines), the polarity of the applied voltage has reversed. Now the anode of D2 is positive with respect to ground and the anode of D1 is negative. Now only D2 can conduct. Current now flows, as shown, from ground (center tap), up through the load resistor (R_L), through diode D2 to point B of T1. In the transformer, current flows from point B up through the lower windings and back to ground (center tap). Notice that the current flows across the load resistor (R_L) in the same direction for both halves of the input cycle.

View B represents the output waveform from the full-wave rectifier. The waveform consists of two pulses of current (or voltage) for each cycle of input voltage. The ripple frequency at the output of the full-wave rectifier is therefore twice the line frequency.

The higher frequency at the output of a full-wave rectifier offers a distinct advantage: Because of the higher ripple frequency, the output is closely approximate to pure dc. The higher frequency also makes filtering much easier than it is for the output of the half-wave rectifier.

In terms of peak value, the average value of current and voltage at the output of the full-wave rectifier is twice as great as that at the output of the half-wave rectifier. The relationship between the peak value and the average value is illustrated in figure 4-7. Since the output waveform is essentially a sine wave with both alternations at the same polarity, the average current or voltage is 63.7 percent (or 0.637) of the peak current or voltage.

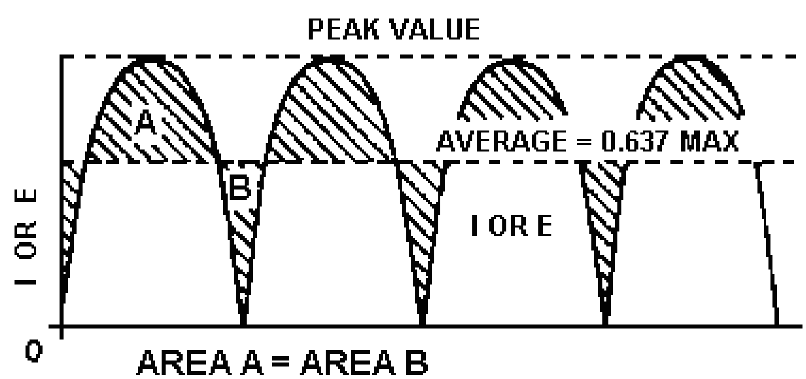


Figure 4-7.—Peak and average values for a full-wave rectifier.

As an equation:

Where:

E_{max} = The peak value of the load voltage pulse

$E_{avg} = 0.637 \times E_{max}$ (the average load voltage)

I_{max} = The peak value of the load current pulse

$I_{avg} = 0.637 \times I_{max}$ (the average load current)

Example: The total voltage across the high-voltage secondary of a transformer used to supply a full-wave rectifier is 300 volts. Find the average load voltage (ignore the drop across the diode).

Solution: Since the total secondary voltage (E_S) is 300 volts, each diode is supplied one-half of this value, or 150 volts. Because the secondary voltage is an rms value, the peak load voltage is:

$$E_{max} = 1.414 \times E_S$$

$$E_{max} = 1.414 \times 150$$

$$E_{max} = 212 \text{ volts}$$

The average load voltage is:

$$E_{avg} = 0.637 \times E_{max}$$

$$E_{avg} = 0.637 \times 212$$

$$E_{avg} = 135 \text{ volts}$$

NOTE: If you have problems with this equation, review the portion of *NEETS*, module 2, that pertain to this subject.

As you may recall from your past studies in electricity, every circuit has advantages and disadvantages. The full-wave rectifier is no exception. In studying the full-wave rectifier, you may have found that by doubling the output frequency, the average voltage has doubled, and the resulting signal is much easier to filter because of the high ripple frequency. The only disadvantage is that the peak voltage in the full-wave rectifier is only half the peak voltage in the half-wave rectifier. This is because the secondary of the power transformer in the full-wave rectifier is center tapped; therefore, only half the source voltage goes to each diode.

Fortunately, there is a rectifier which produces the same peak voltage as a half-wave rectifier and the same ripple frequency as a full-wave rectifier. This circuit, known as the BRIDGE RECTIFIER, will be the subject of our next discussion.

Q8. What was the major factor that led to the development of the full-wave rectifier?

Q9. What is the ripple frequency of a full-wave rectifier with an input frequency of 60 Hz?

Q10. What is the average voltage (E_{avg}) Output of a full-wave rectifier with an output of 100 volts peak?

The Bridge Rectifier

When four diodes are connected as shown in figure 4-8, the circuit is called a BRIDGE RECTIFIER. The input to the circuit is applied to the diagonally opposite corners of the network, and the output is taken from the remaining two corners.

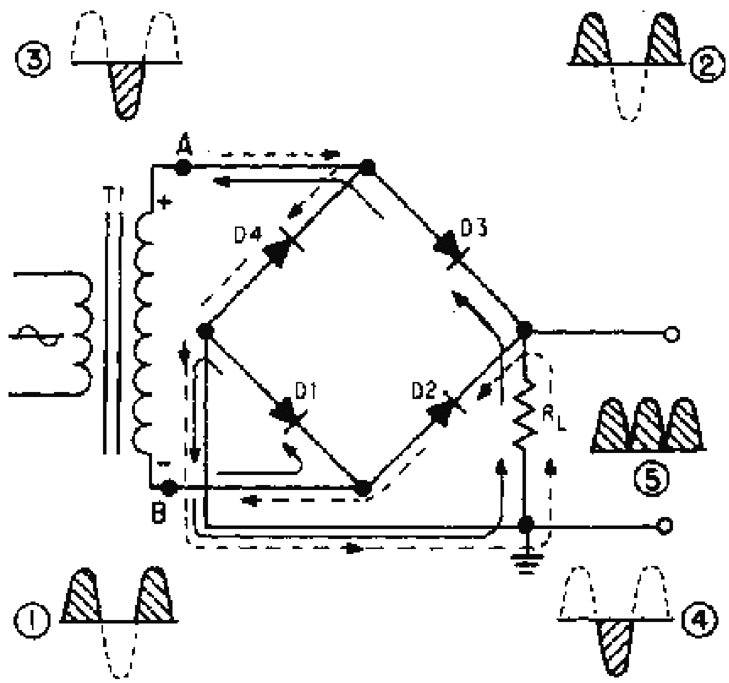


Figure 4-8.—Bridge rectifier.

One complete cycle of operation will be discussed to help you understand how this circuit works. We have discussed transformers in previous modules in the *NEETS* series and will not go into their characteristics at this time. Let us assume the transformer is working properly and there is a positive potential at point A and a negative potential at point B. The positive potential at point A will forward bias D3 and reverse bias D4. The negative potential at point B will forward bias D1 and reverse bias D2. At this time D3 and D1 are forward biased and will allow current flow to pass through them; D4 and D2 are reverse biased and will block current flow. The path for current flow is from point B through D1, up through R_L, through D3, through the secondary of the transformer back to point B. This path is indicated by the solid arrows. Waveforms (1) and (2) can be observed across D1 and D3.

One-half cycle later the polarity across the secondary of the transformer reverses, forward biasing D2 and D4 and reverse biasing D1 and D3. Current flow will now be from point A through D4, up through R_L, through D2, through the secondary of T1, and back to point A. This path is indicated by the broken arrows. Waveforms (3) and (4) can be observed across D2 and D4. You should have noted that the current flow through R_L is always in the same direction. In flowing through R_L this current develops a voltage corresponding to that shown in waveform (5). Since current flows through the load (R_L) during both half cycles of the applied voltage, this bridge rectifier is a full-wave rectifier.

One advantage of a bridge rectifier over a conventional full-wave rectifier is that with a given transformer the bridge rectifier produces a voltage output that is nearly twice that of the conventional full-wave circuit. This may be shown by assigning values to some of the components shown in views A and B of figure 4-9. Assume that the same transformer is used in both circuits. The peak voltage developed between points X and Y is 1000 volts in both circuits. In the conventional full-wave circuit shown in view A, the peak voltage from the center tap to either X or Y is 500 volts. Since only one diode can conduct at any instant, the maximum voltage that can be rectified at any instant is 500 volts. Therefore, the maximum voltage that appears across the load resistor is nearly — but never exceeds — 500 volts, as a result of the small voltage drop across the diode. In the bridge rectifier shown in view B, the maximum voltage that can be rectified is the full secondary voltage, which is 1000 volts. Therefore, the peak output voltage across the load resistor is nearly 1000 volts. With both circuits using the same transformer, the bridge rectifier circuit produces a higher output voltage than the conventional full-wave rectifier circuit.

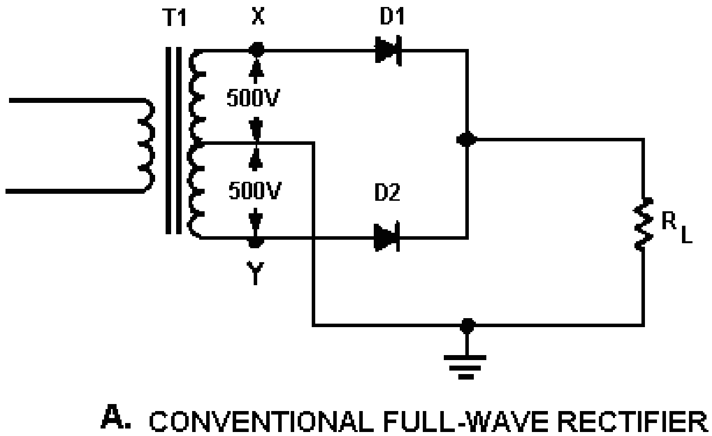


Figure 4-9A.—Comparison of a conventional and bridge full-wave rectifier. CONVENTIONAL FULL-WAVE RECTIFIER

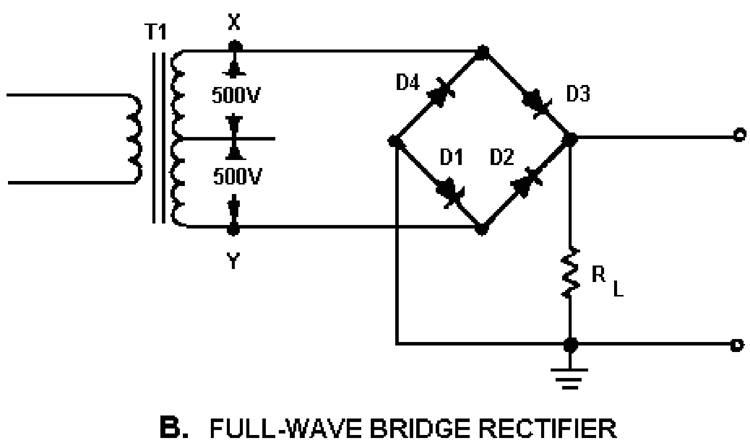


Figure 4-9B.—Comparison of a conventional and bridge full-wave rectifier. FULL-WAVE BRIDGE RECTIFIER

Q11. What is the main disadvantage of a conventional full-wave rectifier?

Q12. What main advantage does a bridge rectifier have over a conventional full-wave rectifier?

FILTERS

While the output of a rectifier is a pulsating dc, most electronic circuits require a substantially pure dc for proper operation. This type of output is provided by single or multisection filter circuits placed between the output of the rectifier and the load.

There are four basic types of filter circuits:

- Simple capacitor filter
- LC choke-input filter

- LC capacitor-input filter (pi-type)
- RC capacitor-input filter (pi-type)

The function of each of these filters will be covered in detail in this chapter.

Filtering is accomplished by the use of capacitors, inductors, and/or resistors in various combinations. Inductors are used as series impedances to oppose the flow of alternating (pulsating dc) current. Capacitors are used as shunt elements to bypass the alternating components of the signal around the load (to ground). Resistors are used in place of inductors in low current applications.

Let's briefly review the properties of a capacitor. First, a capacitor opposes any change in voltage. The opposition to a change in current is called capacitive reactance (X_C) and is measured in ohms. The capacitive reactance is determined by the frequency (f) of the applied voltage and the capacitance (C) of the capacitor.

$$X_C = \frac{1}{2\pi fC} \text{ or } \frac{.159}{fC}$$

From the formula, you can see that if frequency or capacitance is increased, the X_C decreases. Since filter capacitors are placed in parallel with the load, a low X_C will provide better filtering than a high X_C. For this to be accomplished, a better shunting effect of the ac around the load is provided, as shown in figure 4-10.

To obtain a steady dc output, the capacitor must charge almost instantaneously to the value of applied voltage. Once charged, the capacitor must retain the charge as long as possible. The capacitor must have a short charge time constant (view A). This can be accomplished by keeping the internal resistance of the power supply as small as possible (fast charge time) and the resistance of the load as large as possible (for a slow discharge time as illustrated in view B).

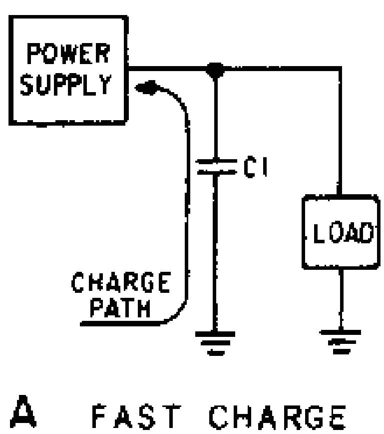


Figure 4-10A.—Capacitor filter. FAST CHARGE

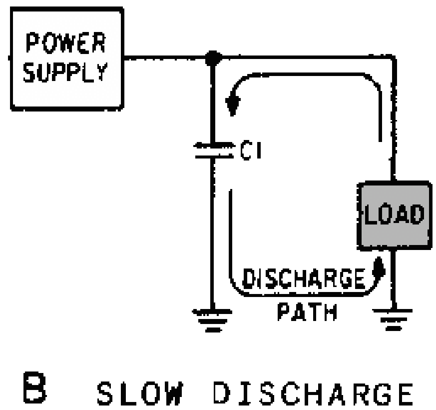


Figure 4-10B.—Capacitor filter. SLOW DISCHARGE

From your earlier studies in basic electricity, you may remember that one time constant is defined as the time it takes a capacitor to charge to 63.2 percent of the applied voltage or to discharge to 36.8 percent of its total charge. This action can be expressed by the following equation:

$$t = RC$$

Where: R represents the resistance of the charge or discharge path

And: C represents the capacitance of the capacitor.

You should also recall that a capacitor is considered fully charged after five RC time constants. Refer to figure 4-11. You can see that a steady dc output voltage is obtained when the capacitor charges rapidly and discharges as slowly as possible.

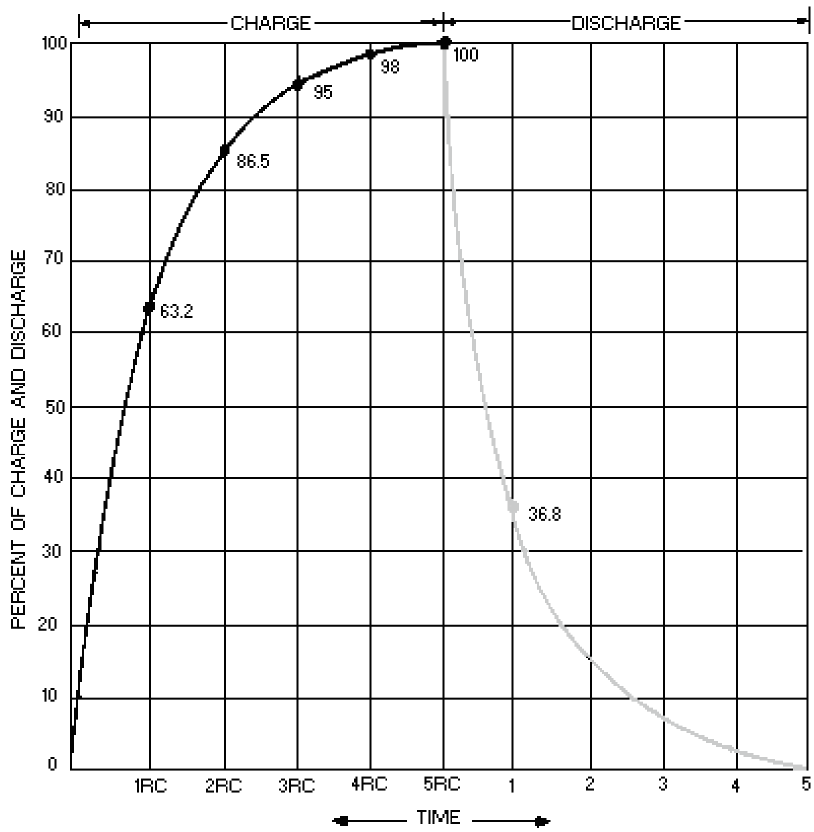


Figure 4-11.—RC time constant.

In filter circuits the capacitor is the common element to both the charge and the discharge paths. Therefore, to obtain the longest possible discharge time, you want the capacitor to be as large as possible. Another way to look at it is: The capacitor acts as a short circuit around the load (as far as the ac component is concerned), and since

$$X_C = \frac{1}{2\pi fC}$$

the larger the value of the capacitor (C), the smaller the opposition (X_C) or reactance to ac.

Now let's look at inductors and their application in filter circuits. Remember, AN INDUCTOR OPPOSES ANY CHANGE IN CURRENT. In case you have forgotten, a change in current through an inductor produces a changing electromagnetic field. The changing field, in turn, cuts the windings of the wire in the inductor and thereby produces a counter electromotive force (CEMF). It is the CEMF that opposes the change in circuit current. Opposition to a change in current at a given frequency is called inductive reactance (X_L) and is measured in ohms. The inductive reactance (X_L) of an inductor is determined by the applied frequency and the inductance of the inductor.

Mathematically,

$$X_L = 2\pi fL$$

If frequency or inductance is increased, the X_L increases. Since inductors are placed in series with the load (as shown in figure 4-12), the larger the X_L, the larger the ac voltage developed across the load.

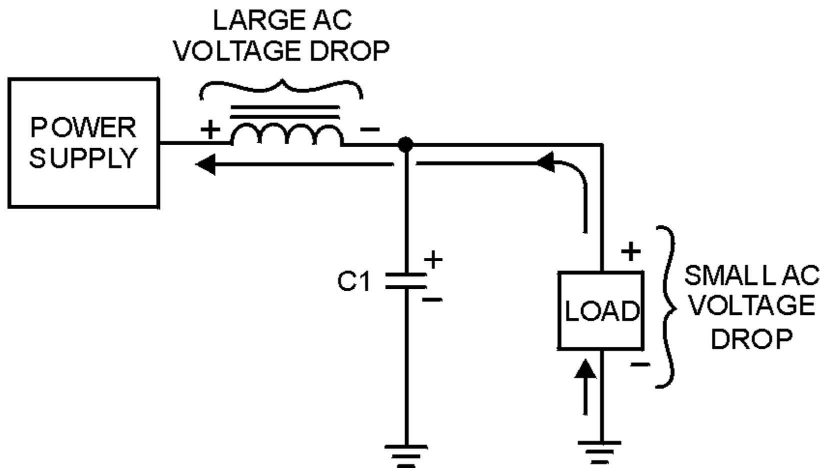


Figure 4-12.—Voltage drops in an inductive filter.

Now refer to figure 4-13. When the current starts to flow through the coil, an expanding magnetic field builds up around the inductor. This magnetic field around the coil develops the CEMF that opposes the change in current. When the rectifier current decreases, as shown in figure 4-14, the magnetic field collapses and again cuts the turns (windings) of wire, thus inducing current into the coil. This additional current merges with the rectifier current and attempts to keep it at its original level.

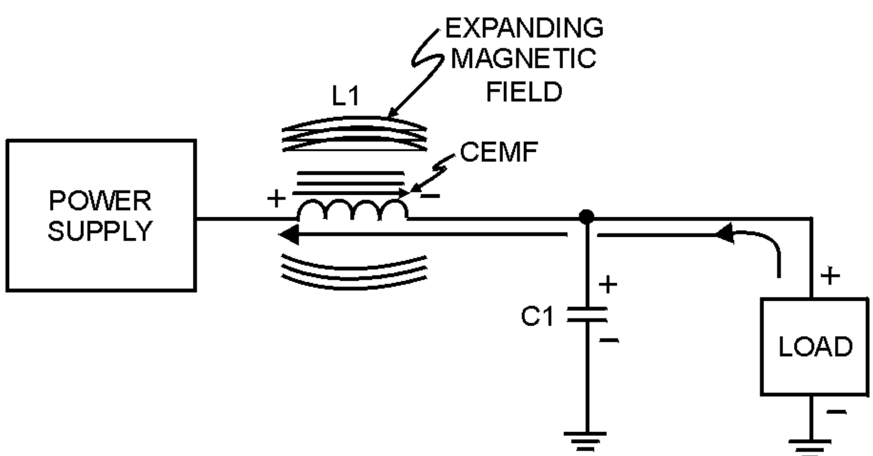


Figure 4-13.—Inductive filter (expanding field).

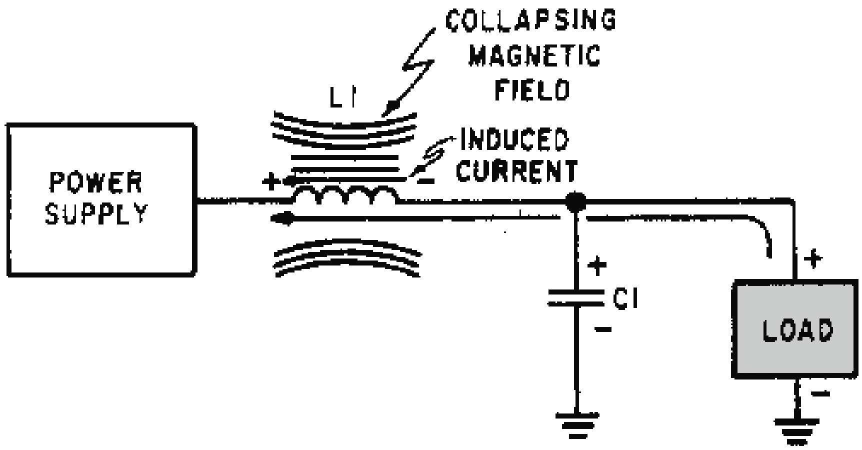


Figure 4-14.—Inductive filter (collapsing field).

Now that you have read how the components in a filter circuit react to current flow from the rectifier, the different types of filter circuits in use today will be discussed.

Q13. If you increase the value of the capacitor, will the X_C increase or decrease? Why?

The Capacitor Filter

The simple capacitor filter is the most basic type of power supply filter. The application of the simple capacitor filter is very limited. It is sometimes used on extremely high-voltage, low-current power supplies for cathode-ray and similar electron tubes, which require very little load current from the supply. The capacitor filter is also used where the power-supply ripple frequency is not critical; this frequency can be relatively high. The capacitor (C1) shown in figure 4-15 is a simple filter connected across the output of the rectifier in parallel with the load.

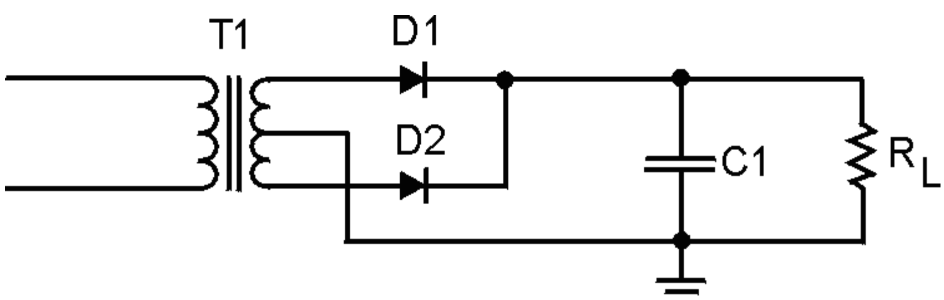
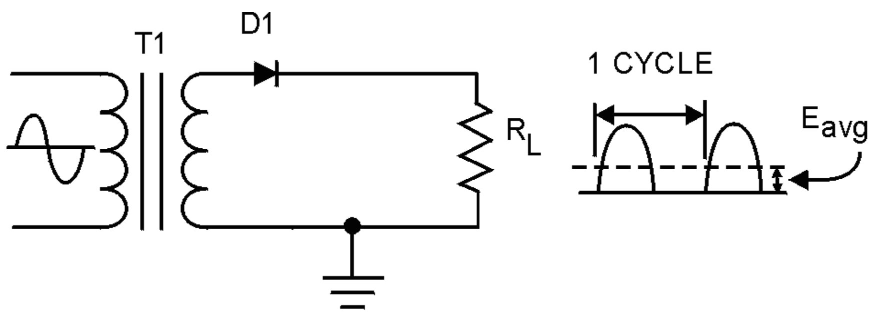


Figure 4-15.—Full-wave rectifier with a capacitor filter.

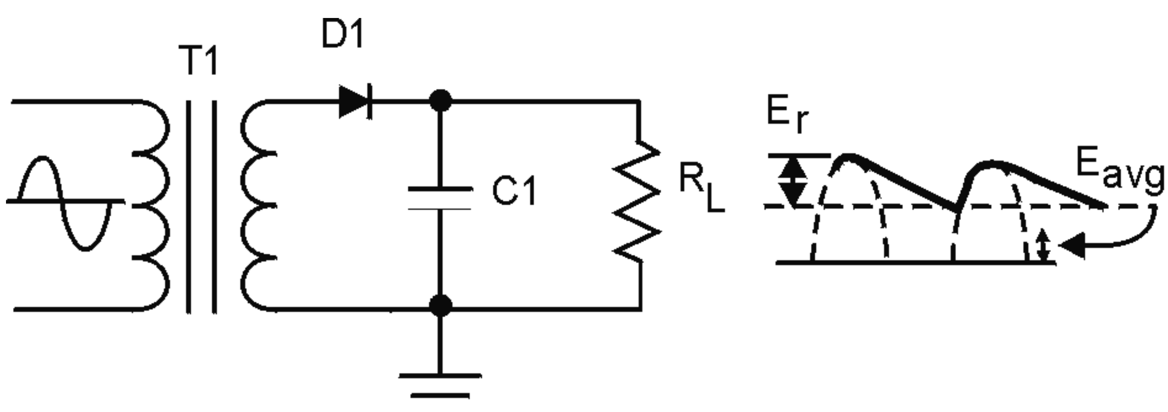
When this filter is used, the RC charge time of the filter capacitor (C1) must be short and the RC discharge time must be long to eliminate ripple action. In other words, the capacitor must charge up fast, preferably with no discharge at all. Better filtering also results when the input frequency is high; therefore, the full-wave rectifier output is easier to filter than that of the half-wave rectifier because of its higher frequency.

For you to have a better understanding of the effect that filtering has on E_{avg}, a comparison of a rectifier circuit with a filter and one without a filter is illustrated in views A and B of figure 4-16. The output waveforms in figure 4-16 represent the unfiltered and filtered outputs of the half-wave rectifier circuit. Current pulses flow through the load resistance (R_L) each time a diode conducts. The dashed line indicates the average value of output voltage. For the half-wave rectifier, E_{avg} is less than half (or approximately 0.318) of the peak output voltage. This value is still much less than that of the applied voltage. With no capacitor connected across the output of the rectifier circuit, the waveform in view A has a large pulsating component (ripple) compared with the average or dc component. When a capacitor is connected across the output (view B), the average value of output voltage (E_{avg}) is increased due to the filtering action of capacitor C1.



A UNFILTERED

Figure 4-16A.—Half-wave rectifier with and without filtering. UNFILTERED



B FILTERED

Figure 4-16B.—Half-wave rectifier with and without filtering. FILTERED

The value of the capacitor is fairly large (several microfarads), thus it presents a relatively low reactance to the pulsating current and it stores a substantial charge.

The rate of charge for the capacitor is limited only by the resistance of the conducting diode which is relatively low. Therefore, the RC charge time of the circuit is relatively short. As a result, when the pulsating voltage is first applied to the circuit, the capacitor charges rapidly and almost reaches the peak value of the rectified voltage within the first few cycles. The capacitor attempts to charge to the peak value of the rectified voltage anytime a diode is conducting, and tends to retain its charge when the rectifier output falls to zero. (The capacitor cannot discharge immediately.) The capacitor slowly discharges through the load resistance (R_L) during the time the rectifier is nonconducting.

The rate of discharge of the capacitor is determined by the value of capacitance and the value of the load resistance. If the capacitance and load-resistance values are large, the RC discharge time for the circuit is relatively long.

A comparison of the waveforms shown in figure 4-16 (view A and view B) illustrates that the addition of C1 to the circuit results in an increase in the average of the output voltage (E_{avg}) and a reduction in the amplitude of the ripple component (E_r) which is normally present across the load resistance.

Now, let's consider a complete cycle of operation using a half-wave rectifier, a capacitive filter (C1), and a load resistor (R_L). As shown in view A of figure 4-17, the capacitive filter (C1) is assumed to be large enough to ensure a small reactance to the pulsating rectified current. The resistance of R_L is assumed to be much greater than the reactance of C1 at the input frequency. When the circuit is energized, the diode conducts on the positive half cycle and current flows through the circuit, allowing C1 to charge. C1 will charge to approximately the peak value of the input voltage. (The charge is less than the peak value because of the voltage drop across the diode (D1)). In view A of the figure, the charge on C1 is indicated by the heavy solid line on the waveform. As illustrated in view B, the diode cannot conduct on the negative half cycle because the anode of D1 is negative with respect to the cathode. During this interval, C1 discharges through the load resistor (R_L). The discharge of C1 produces the downward slope as indicated by the solid line on the waveform in view B. In contrast to the abrupt fall of the applied ac voltage from peak value to zero, the voltage across C1 (and thus across R_L) during the discharge period gradually decreases until the time of the next half cycle of rectifier operation. Keep in mind that for good filtering, the filter capacitor should charge up as fast as possible and discharge as little as possible.

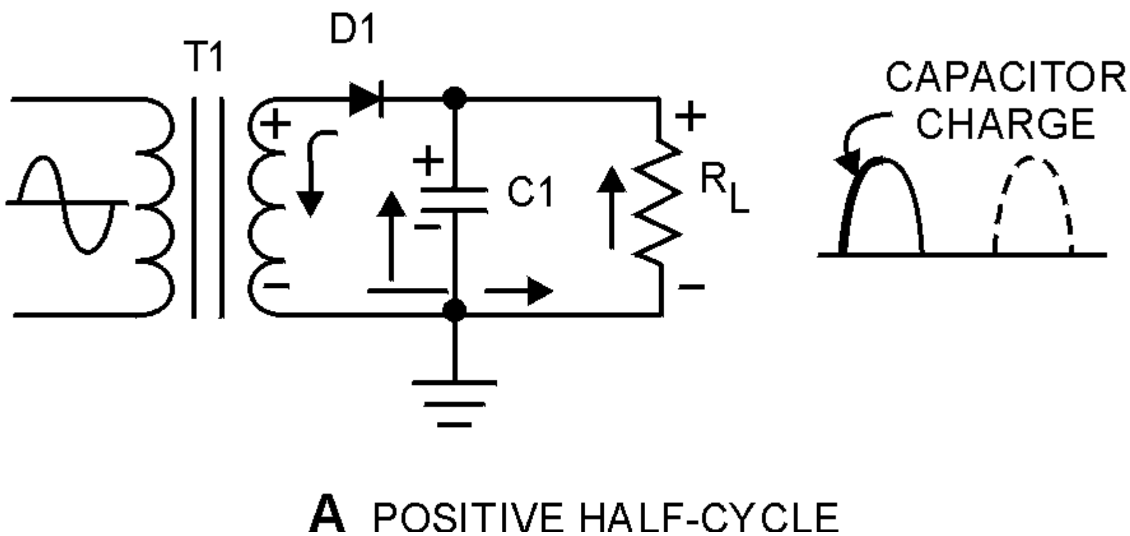


Figure 4-17A.—Capacitor filter circuit (positive and negative half cycles). POSITIVE HALF-CYCLE

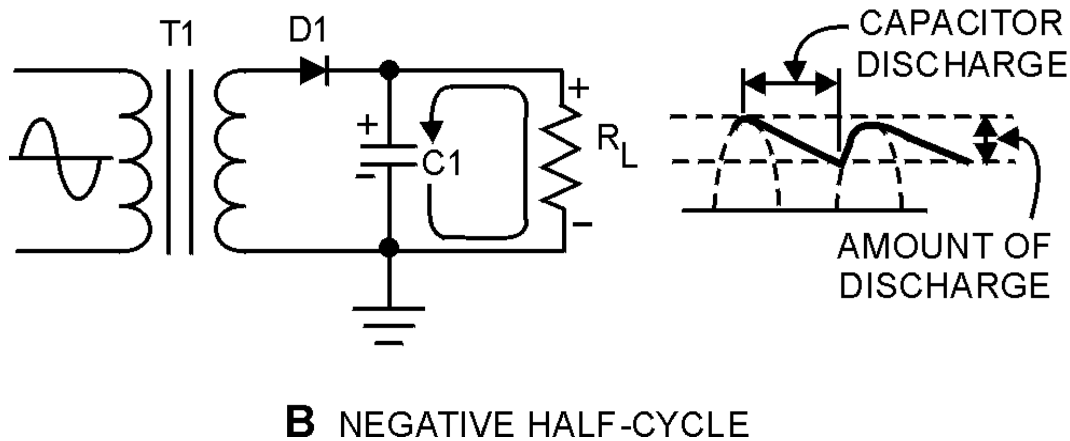


Figure 4-17B.—Capacitor filter circuit (positive and negative half cycles). NEGATIVE HALF-CYCLE

Since practical values of C1 and R_L ensure a more or less gradual decrease of the discharge voltage, a substantial charge remains on the capacitor at the time of the next half cycle of operation. As a result, no current can flow through the diode until the rising ac input voltage at the anode of the diode exceeds the voltage on the charge remaining on C1. The charge on C1 is the cathode potential of the diode. When the potential on the anode exceeds the potential on the cathode (the charge on C1), the diode again conducts, and C1 begins to charge to approximately the peak value of the applied voltage.

After the capacitor has charged to its peak value, the diode will cut off and the capacitor will start to discharge. Since the fall of the ac input voltage on the anode is considerably more rapid than the decrease on the capacitor voltage, the cathode quickly become more positive than the anode, and the diode ceases to conduct.

Operation of the simple capacitor filter using a full-wave rectifier is basically the same as that discussed for the half-wave rectifier. Referring to figure 4-18, you should notice that because one of the diodes is always conducting on. either alternation, the filter capacitor charges and discharges during each half cycle. (Note that each diode conducts only for that portion of time when the peak secondary voltage is greater than the charge across the capacitor.)

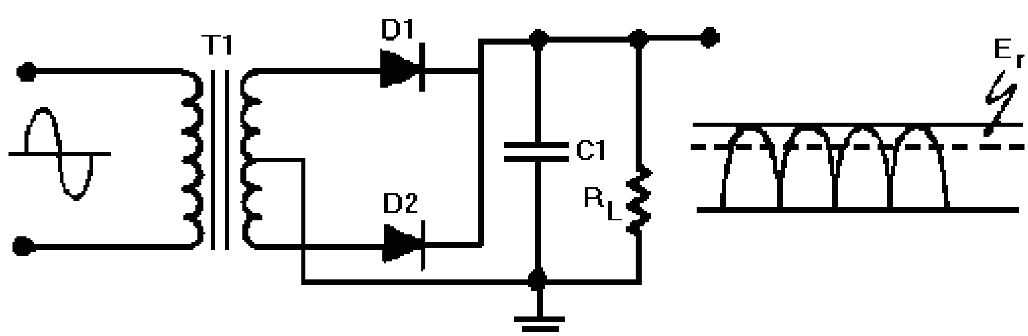


Figure 4-18.—Full-wave rectifier (with capacitor filter).

Another thing to keep in mind is that the ripple component (E) of the output voltage is an ac voltage and the average output voltage (E_{avg}) is the dc component of the output. Since the filter capacitor offers a relatively low impedance to ac, the majority of the ac component flows through the filter capacitor. The ac component is therefore bypassed (shunted) around the load resistance, and the entire dc component (or

E_{avg}) flows through the load resistance. This statement can be clarified by using the formula for X_C in a half-wave and full-wave rectifier. First, you must establish some values for the circuit.

HALFWAVE RECTIFIER

FREQUENCY AT
RECTIFIER OUTPUT: 60 Hz

VALUE OF FILTER
CAPACITOR: 30μF

LOAD RESISTANCE: 10kΩ

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{.159}{fC}$$

$$X_C = \frac{.159}{60 \times .000030}$$

$$X_C = \frac{.159}{.0018}$$

$$X_C = 88.3\Omega$$

FREQUENCY AT
RECTIFIER OUTPUT: 120Hz

VALUE OF FILTER
CAPACITOR: 30μF

LOAD RESISTANCE: 10kΩ

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{.159}{fC}$$

$$X_C = \frac{.159}{120 \times .000030}$$

$$X_C = \frac{.159}{.0036}$$

$$X_C = 44.16\Omega$$

As you can see from the calculations, by doubling the frequency of the rectifier, you reduce the impedance of the capacitor by one-half. This allows the ac component to pass through the capacitor more easily. As a result, a full-wave rectifier output is much easier to filter than that of a half-wave rectifier. Remember, the smaller the X_C of the filter capacitor with respect to the load resistance, the better the filtering action. Since

$$X_C = \frac{1}{2\pi fC}$$

the largest possible capacitor will provide the best filtering. Remember, also, that the load resistance is an important consideration. If load resistance is made small, the load current increases, and the average value of output voltage (E_{avg}) decreases. The RC discharge time constant is a direct function of the value of the load resistance; therefore, the rate of capacitor voltage discharge is a direct function of the current through the load. The greater the load current, the more rapid the discharge of the capacitor, and the lower the average value of output voltage. For this reason, the simple capacitive filter is seldom used with rectifier circuits that must supply a relatively large load current. Using the simple capacitive filter in conjunction with a full-wave or bridge rectifier provides improved filtering because the increased ripple frequency decreases the capacitive reactance of the filter capacitor.

Q14. What is the most basic type of filter?

Q15. In a capacitor filter, is the capacitor in series or in parallel with the load?

Q16. Is filtering better at a high frequency or at a low frequency?

Q17. Does a filter circuit increase or decrease the average output voltage?

Q18. What determines the rate of discharge of the capacitor in a filter circuit?

Q19. Does low ripple voltage indicate good or bad filtering?

Q20. Is a full-wave rectifier output easier to filter than that of a half-wave rectifier?

LC Choke-Input Filter

The LC choke-input filter is used primarily in power supplies where voltage regulation is important and where the output current is relatively high and subject to varying load conditions. This filter is used in high power applications such as those found in radars and communication transmitters.

Notice in figure 4-19 that this filter consists of an input inductor (L1), or filter choke, and an output filter capacitor (C1). Inductor L1 is placed at the input to the filter and is in series with the output of the rectifier circuit. Since the action of an inductor is to oppose any change in current flow, the inductor tends to keep a constant current flowing to the load throughout the complete cycle of the applied voltage. As a result, the output voltage never reaches the peak value of the applied voltage. Instead, the output voltage approximates the average value of the rectified input to the filter, as shown in the figure. The reactance of the inductor (X_L) reduces the amplitude of ripple voltage without reducing the dc output voltage by an appreciable amount. (The dc resistance of the inductor is just a few ohms.)

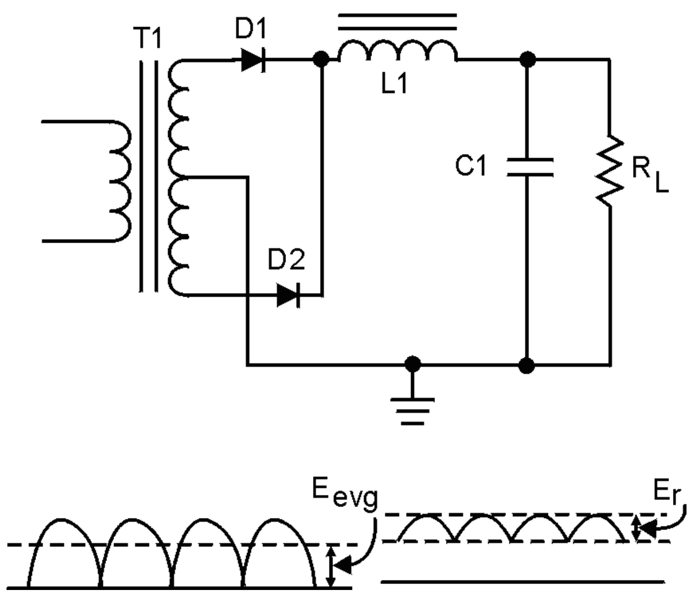


Figure 4-19.—LC choke-input filter.

The shunt capacitor (C1) charges and discharges at the ripple frequency rate, but the amplitude of the ripple voltage (E_r) is relatively small because the inductor (L1) tends to keep a constant current flowing from the rectifier circuit to the load. In addition, the reactance of the shunt capacitor (X_C) presents a low impedance to the ripple component existing at the output of the filter, and thus shunts the ripple component around the load. The capacitor attempts to hold the output voltage relatively constant at the average value of the voltage.

The value of the filter capacitor (C1) must be relatively large to present a low opposition (X_C) to the pulsating current and to store a substantial charge. The rate of the charge for the capacitor is limited by the low impedance of the ac source (the transformer), by the small resistance of the diode, and by the counter electromotive force (CEMF) developed by the coil. Therefore, the RC charge time constant is short compared to its discharge time. (This comparison in RC charge and discharge paths is illustrated in views A and B of figure 4-20.) Consequently, when the pulsating voltage is first applied to the LC choke-input filter, the inductor (L1) produces a CEMF which opposes the constantly increasing input voltage. The net result is to effectively prevent the rapid charging of the filter capacitor (C1). Thus, instead of reaching the peak value of the input voltage, C1 only charges to the average value of the input voltage. After the input voltage reaches its peak and decreases sufficiently, the capacitor C1) attempts to discharge through the load resistance R_L). C1 will only partially discharge, as indicated in view B of the figure, because of its relatively long discharge time constant. The larger the value of the filter capacitor, the better the filtering action. However, because of physical size, there is a practical limitation to the maximum value of the capacitor.

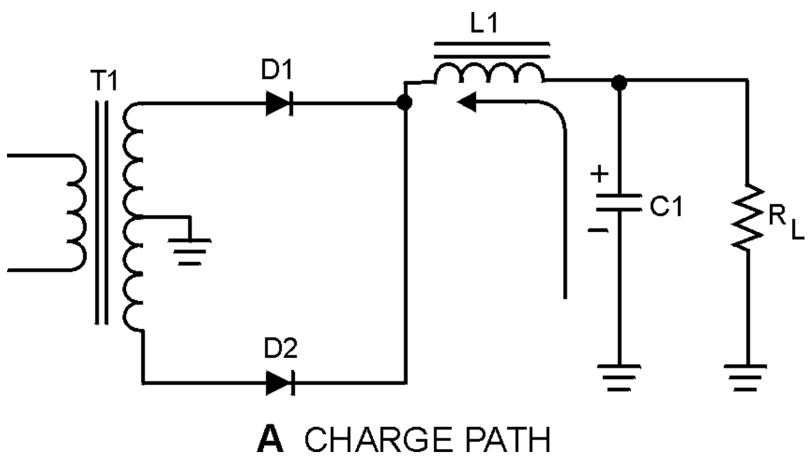


Figure 4-20A.—LC choke-input filter (charge and discharge paths). CHARGE PATH

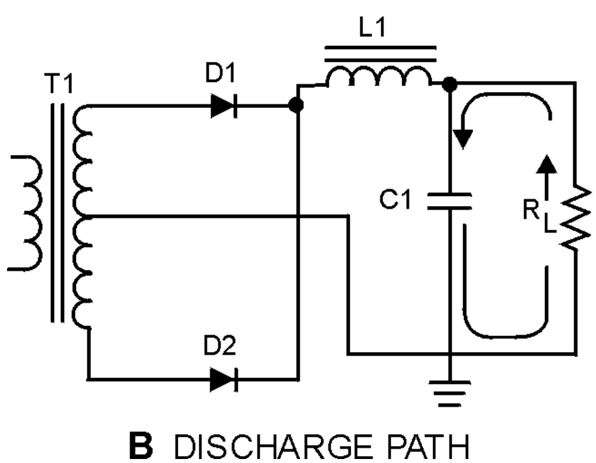


Figure 4-20B.—LC choke-input filter (charge and discharge paths). DISCHARGE PATH

The inductor (also referred to as the filter choke or coil) serves to maintain the current flow to the filter output (R_L) at a nearly constant level during the charge and discharge periods of the filter capacitor. The inductor (L1) and the capacitor (C1) form a voltage divider for the ac component (ripple) of the applied input voltage. This is shown in views A and B of figure 4-21. As far as the ripple component is concerned, the inductor offers a high impedance (Z) and the capacitor offers a low impedance (view B). As a result, the ripple component (E_r) appearing across the load resistance is greatly attenuated (reduced). The inductance of the filter choke opposes changes in the value of the current flowing through it;

therefore, the average value of the voltage produced across the capacitor contains a much smaller value of ripple component (E_r) than the value of ripple produced across the choke.

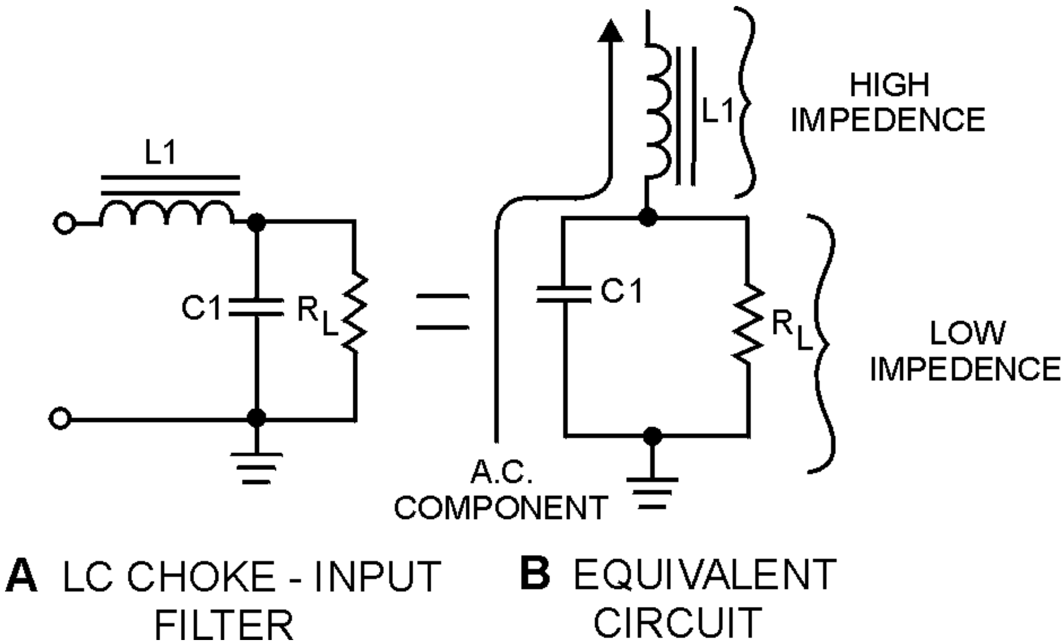


Figure 4-21.—LC choke-input filter.

Now look at figure 4-22 which illustrates a complete cycle of operation for a full-wave rectifier circuit used to supply the input voltage to the filter. The rectifier voltage is developed across the capacitor (C1). The ripple voltage at the output of the filter is the alternating component of the input voltage reduced in amplitude by the filter section. Each time the anode of a diode goes positive with respect to the cathode, the diode conducts and C1 charges. Conduction occurs twice during each cycle for a full-wave rectifier. For a 60-hertz supply, this produces a 120-hertz ripple voltage. Although the diodes alternate (one conducts while the other is nonconducting), the filter input voltage is not steady. As the anode voltage of the conducting diode increases (on the positive half of the cycle), capacitor C1 charges-the charge being limited by the impedance of the secondary transformer winding, the diode's forward (cathode-to-anode) resistance, and the counter electromotive force developed by the choke. During the nonconducting interval (when the anode voltage drops below the capacitor charge voltage), C1 discharges through the load resistor (R_L). The components in the discharge path have a long time constant; thus, C1 discharges more slowly than it charges.

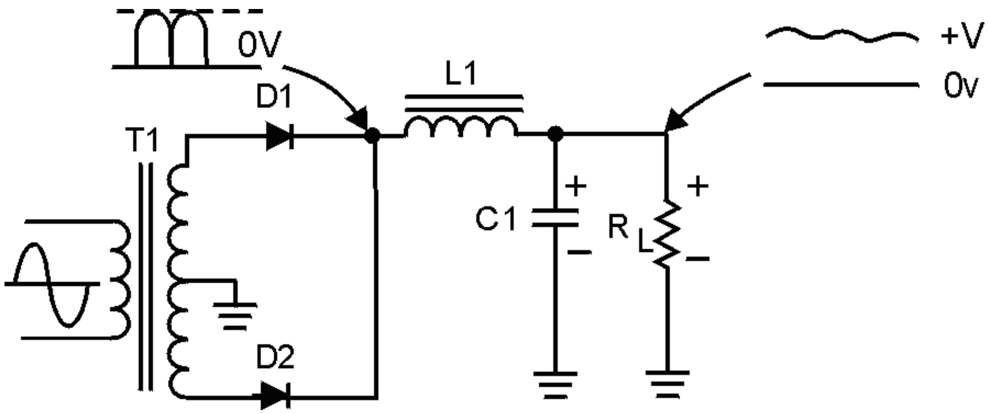


Figure 4-22.—Filtering action of the LC choke-input filter.

The choke (L1) is usually a large value, from 1 to 20 henries, and offers a large inductive reactance to the 120-hertz ripple component produced by the rectifier. Therefore, the effect that L1 has on the charging of the capacitor (C1) must be considered. Since L1 is connected in series with the parallel branch consisting of C1 and R_L, a division of the ripple (ac) voltage and the output (dc) voltage occurs. The greater the impedance of the choke, the less the ripple voltage that appears across C1 and the output. The dc output voltage is fixed mainly by the dc resistance of the choke.

Now that you have read how the LC choke-input filter functions, it will be discussed with actual component values applied. For simplicity, the input frequency at the primary of the transformer will be 117 volts 60 hertz. Both half-wave and full-wave rectifier circuits will be used to provide the input to the filter.

Starting with the half-wave configuration shown in figure 4-23, the basic parameters are: With 117 volts ac rms applied to the T1 primary, 165 volts ac peak is available at the secondary [(117 V) × (1.414) = 165 V]. You should recall that the ripple frequency of this half-wave rectifier is 60 hertz. Therefore, the capacitive reactance of C1 is:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{(2)(3.14)(60)(10)(10^{-6})}$$

$$X_C = \frac{(1)(10^6)}{3768}$$

$$X_C = 265\Omega$$

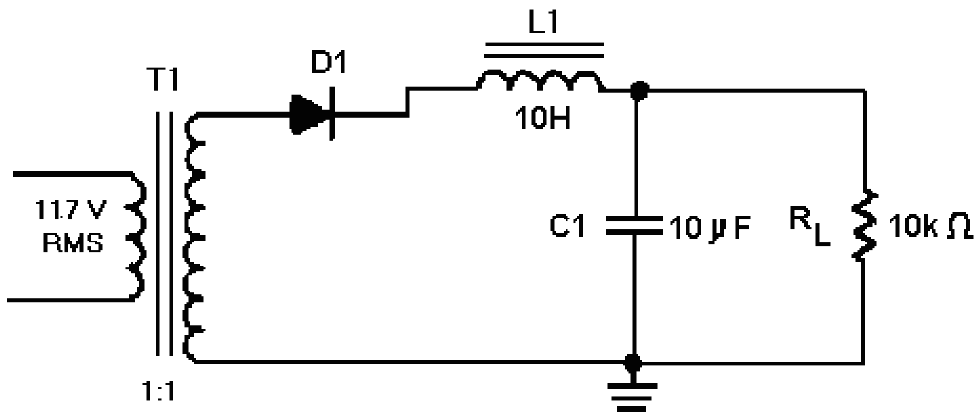


Figure 4-23.—Half-wave rectifier with an LC choke-input filter.

This means that the capacitor (C1) offers 265 ohms of opposition to the ripple current. Note, however, that the capacitor offers an infinite impedance to direct current. The inductive reactance of L1 is:

$$X_L = 2\pi fL$$
$$X_L = (2)(3.14)(60)(10)$$
$$X_L = 3.8 \text{ kilohms}$$

The above calculation shows that L1 offers a relatively high opposition (3.8 kilohms) to the ripple in comparison to the opposition offered by C1 (265 ohms). Thus, more ripple voltage will be dropped across L1 than across C1. In addition, the impedance of C1 (265 ohms) is relatively low with respect to the resistance of the load (10 kilohms). Therefore, more ripple current flows through C1 than the load. In other words, C1 shunts most of the ac component around the load.

Let's go a step further and redraw the filter circuit so that you can see the voltage divider action. Refer to view A of figure 4-24. Remember, the 165 volts peak 60 hertz provided by the rectifier consists of both an ac and a dc component. This first discussion will be about the ac component. From the figure, you see that the capacitor (C1) offers the least opposition (265 ohms) to the ac component. Therefore, the greater amount of ac will flow through C1. (The heavy line in view B indicates the ac current flow through the capacitor.) Thus the capacitor bypasses, or shunts, most of the ac around the load.

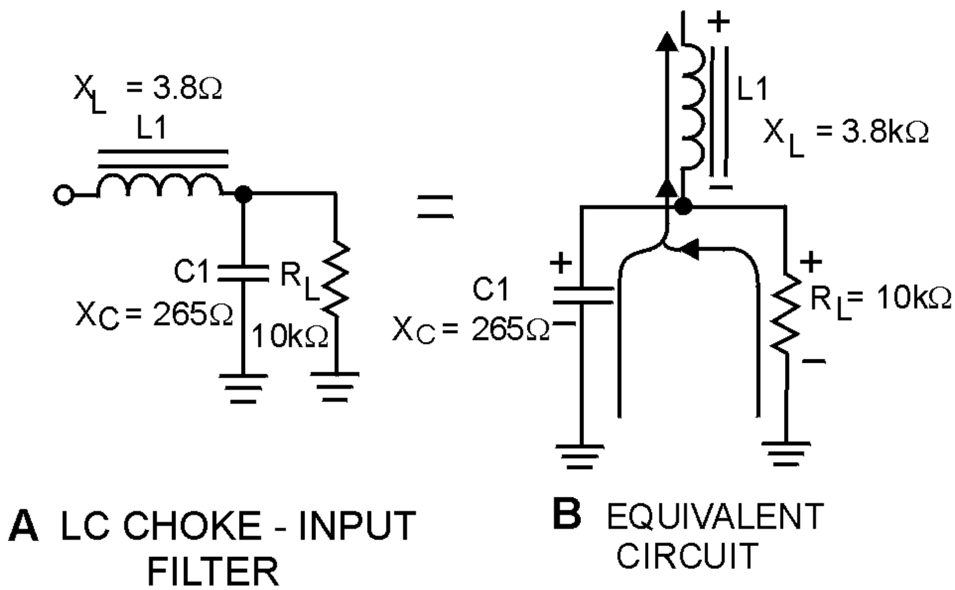


Figure 4-24.—Ac component in an LC choke-input filter.

By combining the X_C of C1 and the resistance of R_L into an equivalent circuit (view B), you will have an equivalent impedance of 265 ohms.

As a formula;

$$RT = \frac{(R1)(R2)}{R1 + R2}$$

You now have a voltage divider as illustrated in figure 4-25. You should see that because of the impedance ratios, a large amount of ripple voltage is dropped across L1, and a substantially smaller amount is dropped across C1 and R_L. You can further increase the ripple voltage across L1 by increasing the inductance ($X_L = 2\pi fL$).

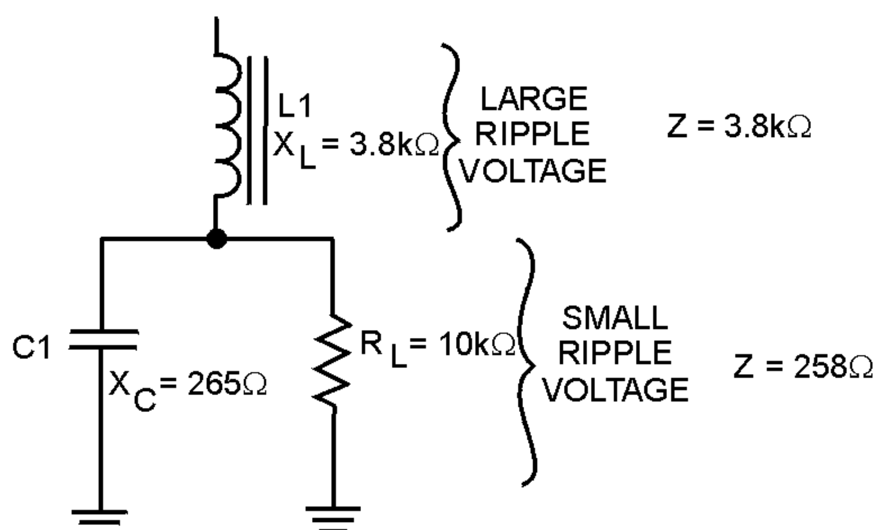


Figure 4-25.—Equivalent circuit of an LC choke-input filter.

Now let's discuss the dc component of the applied voltage. Remember, a capacitor offers an infinite (∞) impedance to the flow of direct current. The dc component, therefore, must flow through R_L and L1. As far as the dc is concerned, the capacitor does not exist. The coil and the load are therefore in series with each other. The dc resistance of a filter choke is very low (50 ohms average). Consequently, most of the dc component is developed across the load and a very small amount of the dc voltage is dropped across the coil, as shown in figure 4-26.

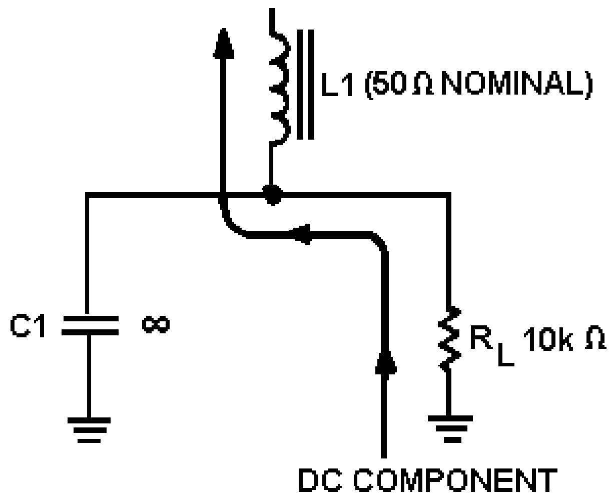


Figure 4-26.—Dc component in an LC choke-input filter.

As you may have noticed, both the ac and the dc components flow through L1. Because it is frequency sensitive, the coil provides a large resistance to ac and a small resistance to dc. In other words, the coil opposes any change in current. This property makes the coil a highly desirable filter component. Note that the filtering action of the LC choke-input filter is improved when the filter is used in conjunction with a full-wave rectifier, as shown in figure 4-27. This is due to the decrease in the X_C of the filter capacitor and the increase in the X_L of the choke. Remember, ripple frequency of a full-wave rectifier is twice that of a half-wave rectifier. For 60-hertz input, the ripple will be 120 hertz. The X_C of C1 and the X_L of L1 are calculated as follows:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{(2)(3.14)(120)(10)(10^{-6})}$$

$$X_C = \frac{(1)(10^6)}{7536}$$

$$X_C = 132.5\Omega$$

$$X_L = 2\pi fL$$

$$X_L = (2)(3.14)(120)(10)$$

$$X_L = 7.5 \text{ kilohms}$$

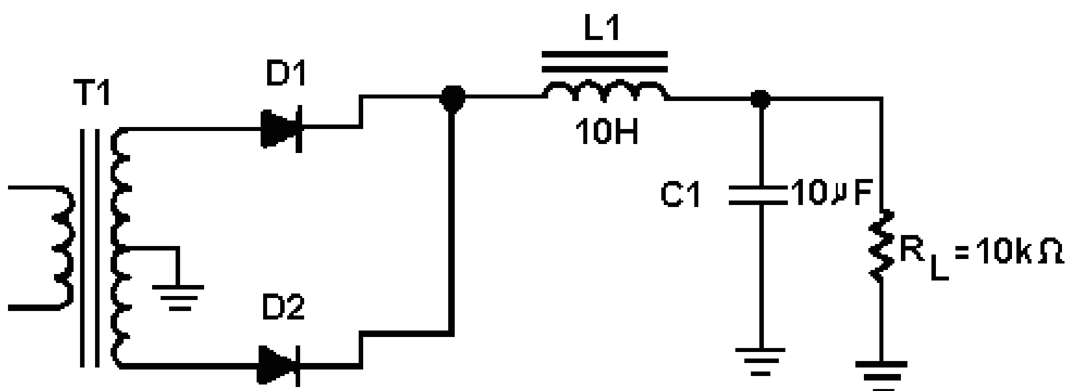


Figure 4-27.—Full-wave rectifier with an LC choke-input filter.

When the X_C of a filter capacitor is decreased, it provides less opposition to the flow of ac. The greater the ac flow through the capacitor, the lower the flow through the load. Conversely, the larger the X_L of the choke, the greater the amount of ac ripple developed across the choke; consequently, less ripple is developed across the load and better filtering is obtained.

Q21. In an LC choke-input filter, what prevents the rapid charging of the capacitor?

Q22. What is the range of values usually chosen for a choke?

Q23. If the impedance of the choke is increased, will the ripple amplitude increase or decrease?

FAILURE ANALYSIS OF AN LC CHOKE-INPUT FILTER.—The filter capacitors are subject to open circuits, short circuits, and excessive leakage; the series inductor is subject to open windings and, occasionally, shorted turns or a short circuit to the core.

The filter capacitor in the LC choke-input filter circuit is not subject to extreme voltage surges because of the protection offered by the inductor. However, the capacitor can become open, leaky, or shorted.

Shorted turns in the choke may reduce the value of inductance below the critical value. This will result in excessive peak-rectifier current, accompanied by an abnormally high output voltage, excessive ripple amplitude, and poor voltage regulation.

A choke winding that is open, or a choke winding which is shorted to the core will result in a no-output condition. A choke winding which is shorted to the core may cause overheating of the rectifier element(s) and blown fuses.

With the supply voltage removed from the input to the filter circuit, one terminal of the capacitor can be disconnected from the circuit. The capacitor should be checked with a capacitance analyzer to determine its capacitance and leakage resistance. When the capacitor is electrolytic, you must use the correct polarity at all times. A decrease in capacitance or losses within the capacitor can decrease the efficiency of the filter and can produce excessive ripple amplitude.

Resistor-Capacitor (RC) Filters

The RC capacitor-input filter is limited to applications in which the load current is small. This type of filter is used in power supplies where the load current is constant and voltage regulation is not necessary. For example, RC filters are used in high-voltage power supplies for cathode-ray tubes and in decoupling networks for multistage amplifiers.

Figure 4-28 shows an RC capacitor-input filter and associated waveforms. Both half-wave and full-wave rectifiers are used to provide the inputs. The waveform shown in view A of the figure represent the unfiltered output from a typical rectifier circuit. Note that the dashed lines in view A indicate the average value of output voltage (E_{avg}) for the half-wave rectifier. The average output voltage (E_{avg}) is less than half (approximately 0.318) the amplitude of the voltage peaks. The average value of output voltage (E_{avg}) for the full-wave rectifier is greater than half (approximately 0.637), but is still much less than, the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component (ripple) as compared to the average (or dc) component.

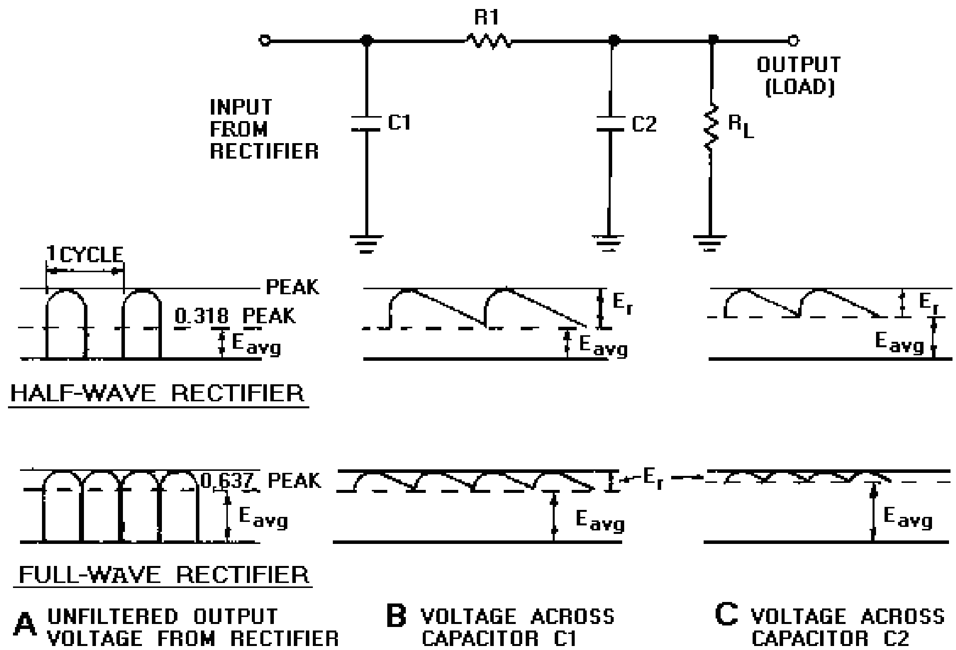


Figure 4-28.—RC filter and waveforms.

The RC filter in figure 4-28 consists of an input filter capacitor (C1), a series resistor (R1), and an output filter capacitor (C2). (This filter is sometimes referred to as an RC pi-section filter because its schematic symbol resembles the Greek letter π).

The single capacitor filter is suitable for many noncritical, low-current applications. However, when the load resistance is very low or when the percent of ripple must be held to an absolute minimum, the capacitor value required must be extremely large. While electrolytic capacitors are available in sizes up to 10,000 microfarads or greater, the large sizes are quite expensive. A more practical approach is to use a more sophisticated filter that can do the same job but that has lower capacitor values, such as the RC filter.

Views A, B, and C of figure 4-28 show the output waveforms of a half-wave and a full-wave rectifier. Each waveform is shown with an RC filter connected across the output. The following explanation of how a filter works will show you that an RC filter of this type does a much better job than the single capacitor filter.

C1 performs exactly the same function as it did in the single capacitor filter. It is used to reduce the percentage of ripple to a relatively low value. Thus, the voltage across C1 might consist of an average dc value of +100 volts with a ripple voltage of 10 volts peak-to-peak. This voltage is passed on to the R1-C2 network, which reduces the ripple even further.

C2 offers an infinite impedance (resistance) to the dc component of the output voltage. Thus, the dc voltage is passed to the load, but reduced in value by the amount of the voltage drop across R1. However, R1 is generally small compared to the load resistance. Therefore, the drop in the dc voltage by R1 is not a drawback.

Component values are designed so that the resistance of R1 is much greater than the reactance (X_C) of C2 at the ripple frequency. C2 offers a very low impedance to the ac ripple frequency. Thus, the ac ripple senses a voltage divider consisting of R1 and C2 between the output of the rectifier and ground. Therefore, most of the ripple voltage is dropped across R1. Only a trace of the ripple voltage can be seen across C2 and the load. In extreme cases where the ripple must be held to an absolute minimum, a second stage of RC filtering can be added. In practice, the second stage is rarely required. The RC filter is extremely popular because smaller capacitors can be used with good results.

The RC filter has some disadvantages. First, the voltage drop across R1 takes voltage away from the load. Second, power is wasted in R1 and is dissipated in the form of unwanted heat. Finally, if the load resistance changes, the voltage across the load will change. Even so, the advantages of the RC filter overshadow these disadvantages in many cases.

Q24. Why is the use of large value capacitors in filter circuits discouraged?

Q25. When is a second RC filter stage used?

FAILURE ANALYSIS OF THE RESISTOR-CAPACITOR (RC) FILTER.—The shunt capacitors (C1 and C2) are subject to an open circuit, a short circuit, or excessive leakage. The series filter resistor (R1) is subject to changes in value and occasionally opens. Any of these troubles can be easily detected.

The input capacitor (C1) has the greatest pulsating voltage applied to it and is the most susceptible to voltage surges. As a result, the input capacitor is frequently subject to voltage breakdown and shorting. The remaining shunt capacitor (C2) in the filter circuit is not subject to voltage surges because of the protection offered by the series filter resistor (R1). However, a shunt capacitor can become open, leaky, or shorted.

A shorted capacitor or an open filter resistor results in a no-output indication. An open filter resistor results in an abnormally high dc voltage at the input to the filter and no voltage at the output of the filter. Leaky capacitors or filter resistors that have lost their effectiveness, or filter resistors that have decreased in value, result in an excessive ripple amplitude in the output of the supply.

LC Capacitor-Input Filter

The LC capacitor-input filter is one of the most commonly used filters. This type of filter is used primarily in radio receivers, small audio amplifier power supplies, and in any type of power supply where the output current is low and the load current is relatively constant.

Figure 4-29 shows an LC capacitor-input filter and associated waveforms. Both half-wave and full-wave rectifier circuits are used to provide the input. The waveforms shown in view A of the figure represent the unfiltered output from a typical rectifier circuit. Note that the average value of output voltage (E_{avg}), indicated by the dashed lines, for the half-wave rectifier is less than half the amplitude of the voltage peaks. The average value of output voltage (E_{avg}) for the full-wave rectifier is greater than half, but is still much less than the peak amplitude of the rectifier-output waveform. With no filter connected across the output of the rectifier circuit (which results in unfiltered output voltage), the waveform has a large value of pulsating component (ripple) as compared to the average (or dc) component.

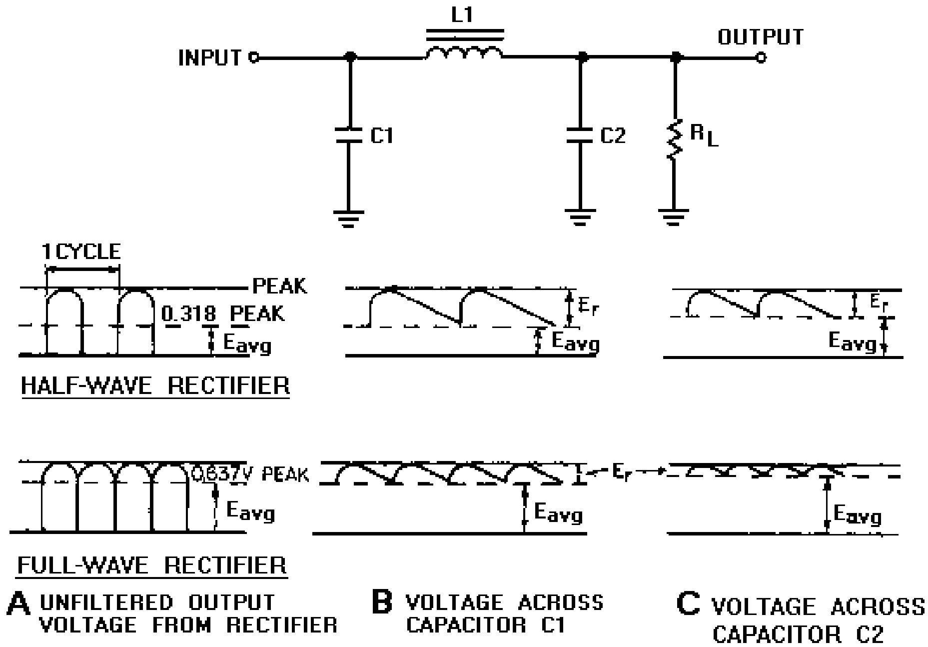


Figure 4-29.—LC filter and waveforms.

C1 reduces the ripple to a relatively low level (view B). L1 and C2 form the LC filter, which reduces the ripple even further. L1 is a large value iron-core induct (choke). L1 has a high value of inductance an therefore, a high value of X_L which offers a high reactance to the ripple frequency. At the same time, C2 offers a very low reactance to ac ripple. L1 and C2 for an ac voltage divider and, because the reactance of L1 much higher than that of C2, most of the ripple voltage is dropped across L1. Only a slight trace of ripple appears across C2 and the load (view C).

While the L1-C2 network greatly reduces ac ripple it has little effect on dc. You should recall that an inductor offers no reactance to dc. The only opposition to current flow is the resistance of the wire in the choke. Generally, this resistance is very low and the dc voltage drop across the coil is minimal. Thus, the LC filter overcomes the disadvantages of the RC filter.

Aside from the voltage divider effect, the inductor improves filtering in another way. You should recall that an inductor resists changes in the magnitude of the current flowing through it. Consequently, when the inductor is placed in series with the load, the inductor maintains steady current. In turn, this helps the voltage across the load remain constant when size of components is a factor.

The LC filter provides good filtering action over a wide range of currents. The capacitor filters best when the load is drawing little current. Thus, the capacitor discharges very slowly and the output voltage remains almost constant. On the other hand, the inductor filters best when the current is highest. The complementary nature of these two components ensures that good filtering will occur over a wide range of currents.

The LC filter has two disadvantages. First, it is more expensive than the RC filter because an iron-core choke costs more than a resistor. The second disadvantage is size. The iron-core choke is bulky and heavy, a fact which may render the LC filter unsuitable for many applications.

Q26. What is the most commonly used filter today?

Q27. What are the two main disadvantages of an LC capacitor filter?

FALURE ANALYSIS OF THE LC CAPACITOR-INPUT FILTER.—Shunt capacitors are subject to open circuits, short circuits, and excessive leakage; series inductors are subject to open windings and occasionally shorted turns or a short circuit to the core.

The input capacitor (C1) has the greatest pulsating voltage applied to it, is the most susceptible to voltage surges, and has a generally higher average voltage applied. As a result, the input capacitor is frequently subject to voltage breakdown and shorting. The output capacitor (C2) is not as susceptible to voltage surges because of the series protection offered by the series inductor (L1), but the capacitor can become open, leaky, or shorted.

A shorted capacitor, an open filter choke, or a choke winding which is shorted to the core, results in a no-output indication. A shorted capacitor, depending on the magnitude of the short, may cause a shorted rectifier, transformer, or filter choke, and may result in a blown fuse in the primary of the transformer. An open filter choke results in an abnormally high dc voltage at the input to the filter and no voltage at the output of the filter. A leaky or open capacitor in the filter circuit results in a low dc output voltage. This condition is generally accompanied by an excessive ripple amplitude. Shorted turns in the winding of a filter choke reduce the effective inductance of the choke and decrease its filtering efficiency. As a result, the ripple amplitude increases.

VOLTAGE REGULATION

Ideally, the output of most power supplies should be a constant voltage. Unfortunately, this is difficult to achieve. There are two factors that can cause the output voltage to change. First, the ac line voltage is not constant. The so-called 115 volts ac can vary from about 105 volts ac to 125 volts ac. This means that the peak ac voltage to which the rectifier responds can vary from about 148 volts to 177 volts. The ac line voltage alone can be responsible for nearly a 20 percent change in the dc output voltage. The second factor that can change the dc output voltage is a change in the load resistance. In complex electronic equipment, the load can change as circuits are switched in and out. In a television receiver, the load on a particular power supply may depend on the brightness of the screen, the control settings, or even the channel selected.

These variations in load resistance tend to change the applied dc voltage because the power supply has a fixed internal resistance. If the load resistance decreases, the internal resistance of the power supply drops more voltage. This causes a decrease in the voltage across the load.

Many circuits are designed to operate with a particular supply voltage. When the supply voltage changes, the operation of the circuit may be adversely affected. Consequently, some types of equipment must have power supplies that produce the same output voltage regardless of changes in the load resistance or changes in the ac line voltage. This constant output voltage may be achieved by adding a circuit called the VOLTAGE REGULATOR at the output of the filter. There are many different types of regulators in use today and to discuss all of them would be beyond the scope of this chapter.

LOAD REGULATION

A commonly used FIGURE OF MERIT for a power supply is its PERCENT OF REGULATION. The figure of merit gives us an indication of how much the output voltage changes over a range of load resistance values. The percent of regulation aids in the determination of the type of load regulation needed. Percent of regulation is determined by the equation:

$$\text{Percent of regulation} = \frac{(E_{nL} - E_{fL})}{E_{fL}} \times 100$$

This equation compares the change in output voltage at the two loading extremes to the voltage produced at full loading. For example, assume that a power supply produces 12 volts when the load current is zero. If the output voltage drops to 10 volts when full load current flows, then the percent of regulation is:

$$\text{Percent of regulation} = \frac{(E_{nL} - E_{fL})}{E_{fL}} \times 100$$

$$\text{Percent of regulation} = \frac{(12 - 10V)}{10V} \times 100$$

$$\text{Percent of regulation} = \frac{2V}{10V} \times 100$$

$$\text{Percent of regulation} = 20\%$$

Ideally, the output voltage should not change over the full range of operation. That is, a 12-volt power supply should produce 12 volts at no load, at full load, and at all points in between. In this case, the percent of regulation would be:

$$\text{Percent of regulation} = \frac{(E_{nL} - E_{fL})}{E_{fL}} \times 100$$

$$\text{Percent of regulation} = \frac{(12 - 12V)}{12V} \times 100$$

$$\text{Percent of regulation} = \frac{0V}{12V} \times 100$$

$$\text{Percent of regulation} = 0\%$$

Thus, zero-percent load regulation is the ideal situation. It means that the output voltage is constant under all load conditions. While you should strive for zero percent load regulation, in practical circuits you must settle for something less ideal. Even so, by using a voltage regulator, you can hold the percent of regulation to a very low value.

REGULATORS

You should know that the output of a power supply varies with changes in input voltage and circuit load current requirements. Because many electronic equipments require operating voltages and currents that must remain constant, some form of regulation is necessary. Circuits that maintain power supply voltages or current outputs within specified limits, or tolerances are called REGULATORS. They are designated as dc voltage or dc current regulators, depending on their specific application.

Voltage regulator circuits are additions to basic power supply circuits, which are made up of rectified and filter sections (figure 4-30). The purpose of the voltage regulator is to provide an output voltage with little or no variation. Regulator circuits sense changes in output voltages and compensate for the changes. Regulators that maintain voltages within plus or minus (±) 0.1 percent are quite common.

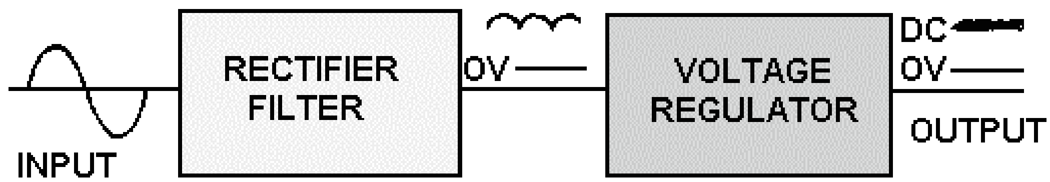


Figure 4-30.—Block diagram of a power supply and regulator.

Series and Shunt Voltage Regulators

There are two basic types of voltage regulators. Basic voltage regulators are classified as either SERIES or SHUNT, depending on the location or position of the regulating element(s) in relation to the circuit load resistance. Figure 4-31 (view A and view B) illustrates these two basic types of voltage regulators. In actual practice the circuitry of regulating devices may be quite complex. Broken lines have been used in the figure to highlight the differences between the series and shunt regulators.

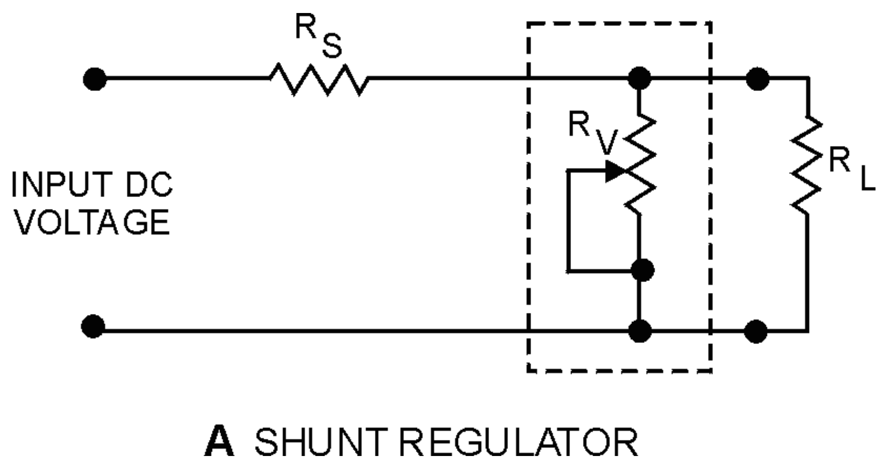


Figure 4-31A.—Simple series and shunt regulators. SHUNT REGULATOR.

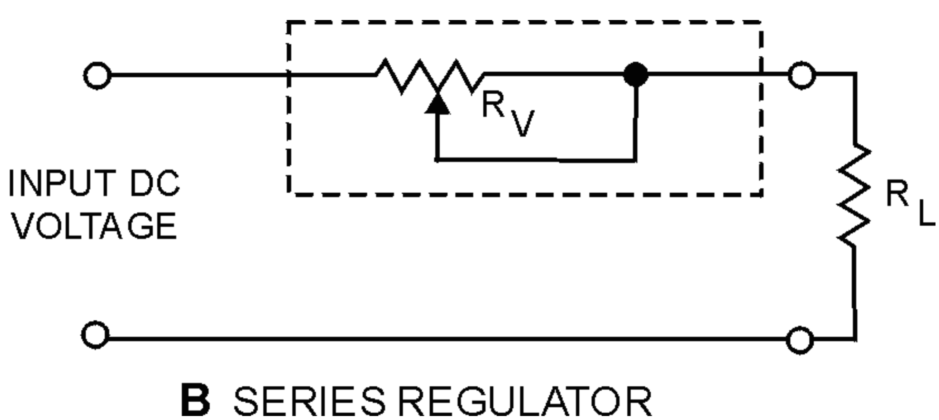


Figure 4-31B.—Simple series and shunt regulators. SERIES REGULATOR.

The schematic drawing in view A is that of a shunt-type regulator. It is called a shunt-type regulator because the regulating device is connected in parallel with the load resistance. The schematic drawing in view B is that of a series regulator. It is called a series regulator because the regulating device is connected in series with the load resistance. Figure 4-32 illustrates the principle of series voltage regulation. As you study the figure, notice that the regulator is in series with the load resistance (R_L) and that the fixed resistor (R_S) is in series with the load resistance.

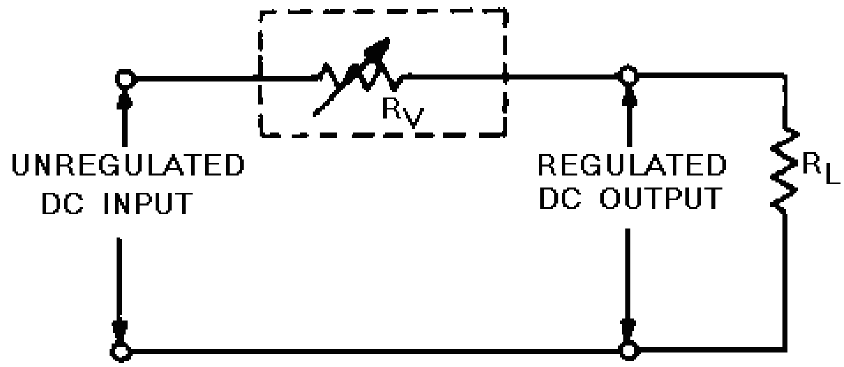


Figure 4-32.—Series voltage regulator.

You already know the voltage drop across a fixed resistor remains constant unless the current flowing through it varies (increases or decreases). In a shunt regulator, as shown in figure 4-33, output voltage regulation is determined by the current through the parallel resistance of the regulating device (R_V), the load resistance (R_L), and the series resistor (R_S). For now, assume that the circuit is operating under normal conditions, that the input is 120 volts dc, and that the desired regulated output is 100 volts dc. For a 100-volt output to be maintained, 20 volts must be dropped across the series resistor (R_S). If you assume that the value of R_S is 2 ohms, you must have 10 amperes of current through R_V and R_L. (Remember: E = IR.) If the values of the resistance of R_V and R_L are equal, 5 amperes of current will flow through each resistance (R_V and R_L).

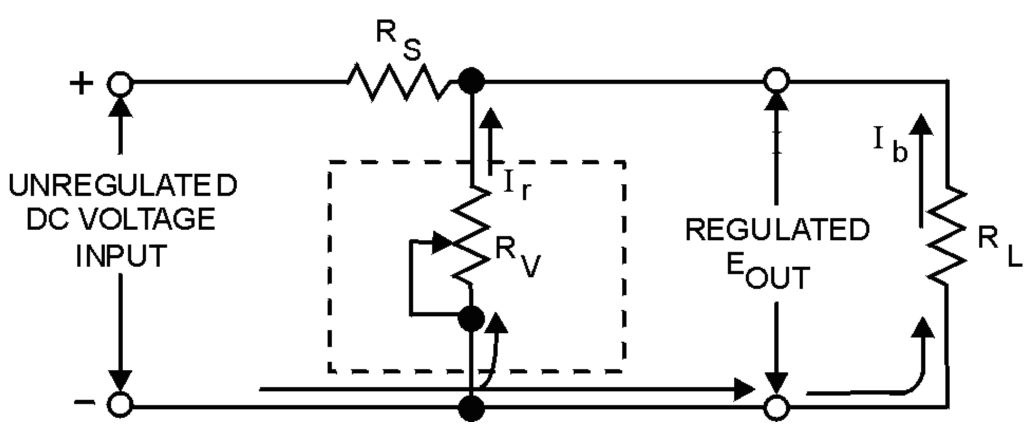


Figure 4-33.—Shunt voltage regulator.

Now, if the load resistance (R_L) increases, the current through R_L will decrease. For example, assume that the current through R_L is now 4 amperes and that the total current through R_S is 9 amperes. With this drop in current, the voltage drop across R_S is 18 volts; consequently, the output of the regulator has increased to 102 volts. At this time, the regulating device (R_V) decreases in resistance, and 6 amperes of current flows through this resistance (R_V). Thus, the total current R_S is once again 10 amperes (6 amperes through R_V; 4 amperes through R_L). Therefore, 20 volts is dropped across R_S causing the output to decrease back to 100 volts. You should know by now that if the load resistance (R_L) increases, the regulating device (R_V) decreases its resistance to compensate for the change. If R_L decreases, the opposite effect occurs and R_V increases.

Now consider the circuit when a decrease in load resistance takes place. When R_L decreases, the current through R_L subsequently increases to 6 amperes. This action causes a total of 11 amperes to flow through R_S which then drops 22 volts. As a result, the output is 98 volts. However, the regulating device (R_V) senses this change and increases its resistance so that less current (4 amperes) flows through R_V. The total current again becomes 10 amperes, and the output is again 100 volts.

From these examples, you should now understand that the shunt regulator maintains the desired output voltage first by sensing the current change in the parallel resistance of the circuit and then by compensating for the change.

Again refer to the schematic shown in figure 4-33 and consider how the voltage regulator operates to compensate for changes in input voltages. You know, of course, that the input voltage may vary and that any variation must be compensated for by the regulating device. If an increase in input voltage occurs, the resistance of R_V automatically decreases to maintain the correct voltage division between R_V and R_S. You should see, therefore, that the regulator operates in the opposite way to compensate for a decrease in input voltage.

So far only voltage regulators that use variable resistors have been explained. However, this type of regulation has limitations. Obviously, the variable resistor cannot be adjusted rapidly enough to compensate for frequent fluctuations in voltages. Since input voltages fluctuate frequently and rapidly, the variable resistor is not a practical method for voltage regulation. A voltage regulator that operates continuously and automatically to regulate the output voltage without external manipulation is required for practical regulation.

Q28. Circuits which maintain constant voltage or current outputs are called dc voltage or dc current ___.

Q29. The purpose of a voltage regulator is to provide an output voltage with little or no ___.

Q30. The two basic types of voltage regulators are ___ and ___.

Q31. When a series voltage regulator is used to control output voltages, any increase in the input voltage results in an increase/a decrease (which one) in the resistance of the regulating device.

Q32. A shunt-type voltage regulator is connected in serial/parallel (which one) with the load resistance.

The schematic for a typical series voltage regulator is shown in figure 4-34. Notice that this regulator has a transistor (Q1) in the place of the variable resistor found in figure 4-32. Because the total load current passes through this transistor, it is sometimes called a "pass transistor." Other components which make up the circuit are the current limiting resistor (R1) and the Zener diode (CR1).

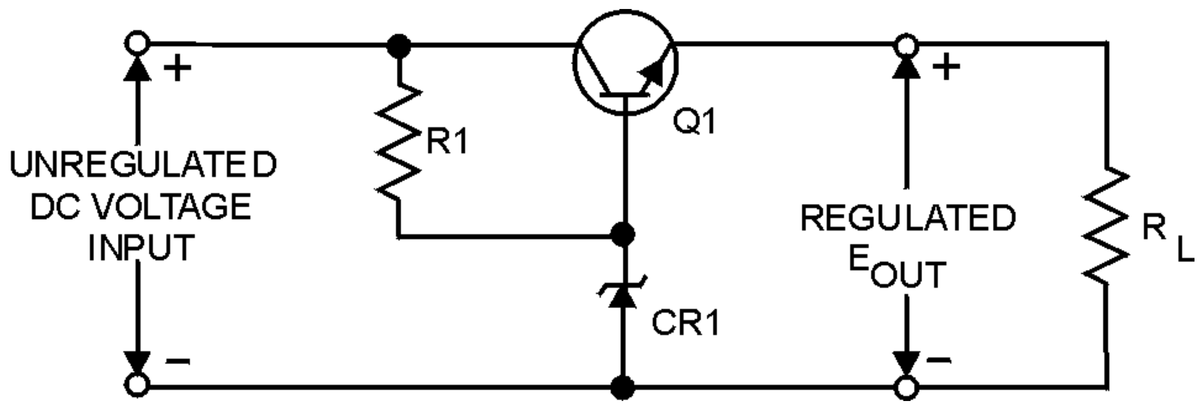


Figure 4-34.—Series voltage regulator.

Recall that a Zener diode is a diode that block current until a specified voltage is applied. Remember also that the applied voltage is called the breakdown, or Zener voltage. Zener diodes are available with different Zener voltages. When the Zener voltage is reached, the Zener diode conducts from its anode to its cathode (with the direction of the arrow).

In this voltage regulator, Q1 has a constant voltage applied to its base. This voltage is often called the reference voltage. As changes in the circuit output voltage occur, they are sensed at the emitter of Q1 producing a corresponding change in the forward bias of the transistor. In other words, Q1 compensates by increasing or decreasing its resistance in order to change the circuit voltage division.

Now, study figure 4-35. Voltages are shown to help you understand how the regulator operates. The Zener used in this regulator is a 15-volt Zener. In this instance the Zener or breakdown voltage is 15 volts. The Zener establishes the value of the base voltage for Q1. The output voltage will equal the Zener voltage minus a 0.7-volt drop across the forward biased base-emitter junction of Q1, or 14.3 volts. Because the output voltage is 14.3 volts, the voltage drop across Q1 must be 5.7 volts.

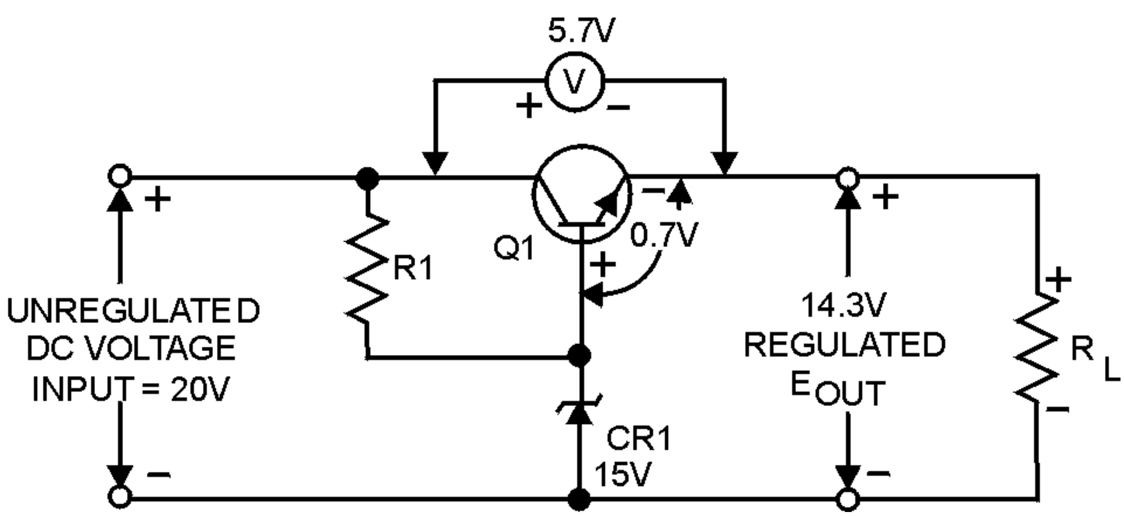


Figure 4-35.—Series voltage regulator (with voltages).

Study figure 4-36, view A, in order to understand what happens when the input voltage exceeds 20 volts. Notice the input and output voltages of 20.1 and 14.4 volts, respectively. The 14.4 output voltage is a momentary deviation, or variation, from the required regulated output voltage of 14.3 and is the result of a rise in the input voltage to 20.1 volts. Since the base voltage of Q1 is held at 15 volts by CR1, the forward bias of Q1 changes to 0.6 volt. Because this bias voltage is less than the normal 0.7 volt, the resistance of Q1 increases, thereby increasing the voltage drop across the transistor to 5.8 volts. This voltage drop restores the output voltage to 14.3 volts. The entire cycle takes only a fraction of a second and, therefore, the change is not visible on an oscilloscope or readily measurable with other standard test equipment.

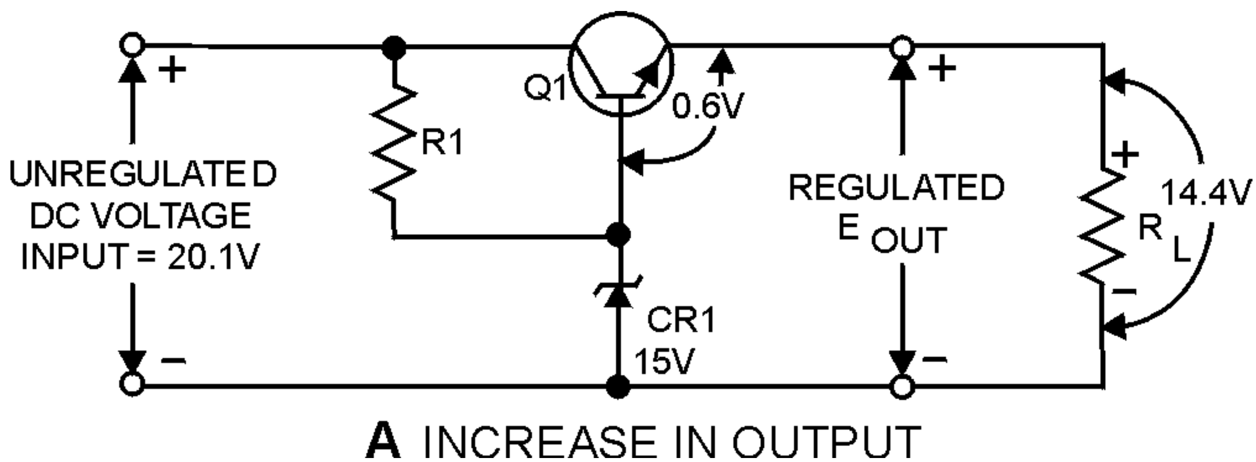


Figure 4-36A.—Series voltage regulator. INCREASE IN OUTPUT

View B is a schematic diagram for the same series voltage regulator with one significant difference. The output voltage is shown as 14.2 volts instead of the desired 14.3 volts. In this case, the load has increased causing a lowered voltage drop across R_L to 14.2 volts. When the output decreases, the forward bias of Q1 increases to 0.8 volt because Zener diode CR1 maintains the base voltage of Q1 at 15 volts. This 0.8 volt is the difference between the Zener reference voltage of 15 volts and the momentary output voltage. (15 V – 14.2 V = 0.8 V). At this point, the larger forward bias on Q1 causes the resistance of Q1 to decrease, thereby causing the voltage drop across Q1 to return to 5.7 volts. This then causes the output voltage to return to 14.3 volts.

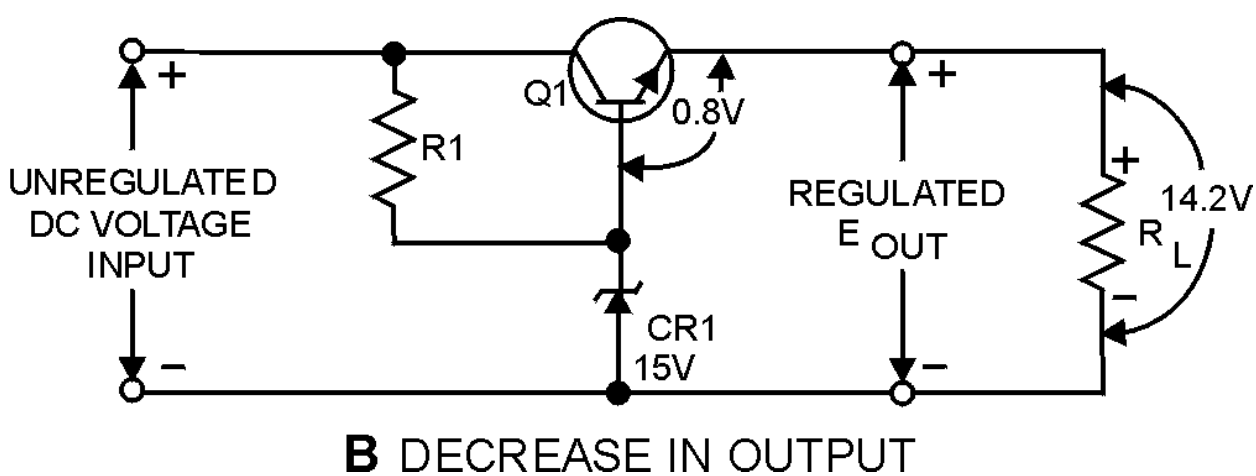


Figure 4-36B.—Series voltage regulator. DECREASE IN OUTPUT

The schematic shown in figure 4-37 is that of a shunt voltage regulator. Notice that Q1 is in parallel with the load. Components of this circuit are identical with those of the series voltage regulator except for the addition of fixed resistor R_S. As you study the schematic, you will see that this resistor is connected in series with the output load resistance. The current limiting resistor (R1) and Zener diode (CR1) provide a constant reference voltage for the base-collector junction of Q1. Notice that the bias of Q1 is determined by the voltage drop across R_S and R1. As you should know, the amount of forward bias across a transistor affects its total resistance. In this case, the voltage drop across R_S is the key to the total circuit operation.

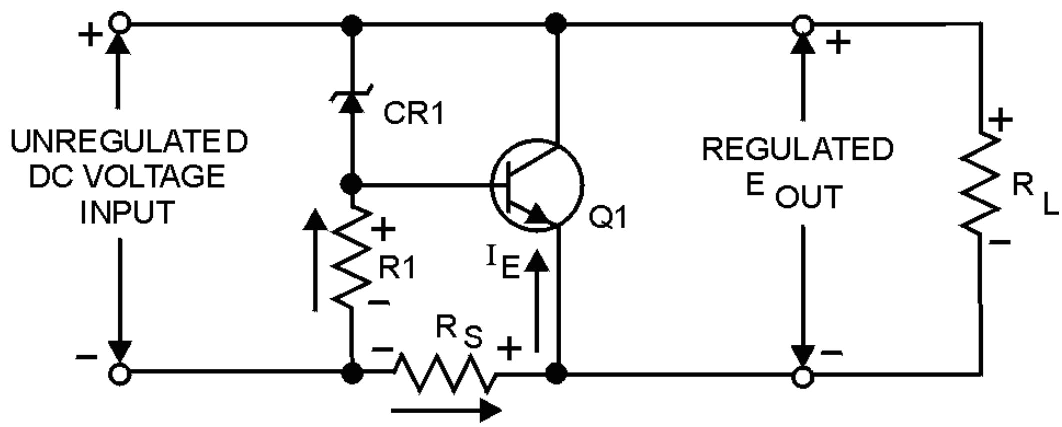


Figure 4-37.—Shunt voltage regulator.

Figure 4-38 is the schematic for a typical shunt-type regulator. Notice that the schematic is identical to the schematic shown in figure 4-37 except that voltages are shown to help you understand the functions of the various components. In the circuit shown, the voltage drop across the Zener diode (CR1) remains constant at 5.6 volts. This means that with a 20-volt input voltage, the voltage drop across R1 is 14.4 volts. With a base-emitter voltage of 0.7 volt, the output voltage is equal to the sum of the voltages across CR1 and the voltage at the base-emitter junction of Q1. In this example, with an output voltage of 6.3 volts and a 20-volt input voltage, the voltage drop across R_S equals 13.7 volts. Study the schematic to understand fully how these voltages are developed. Pay close attention to the voltages shown.

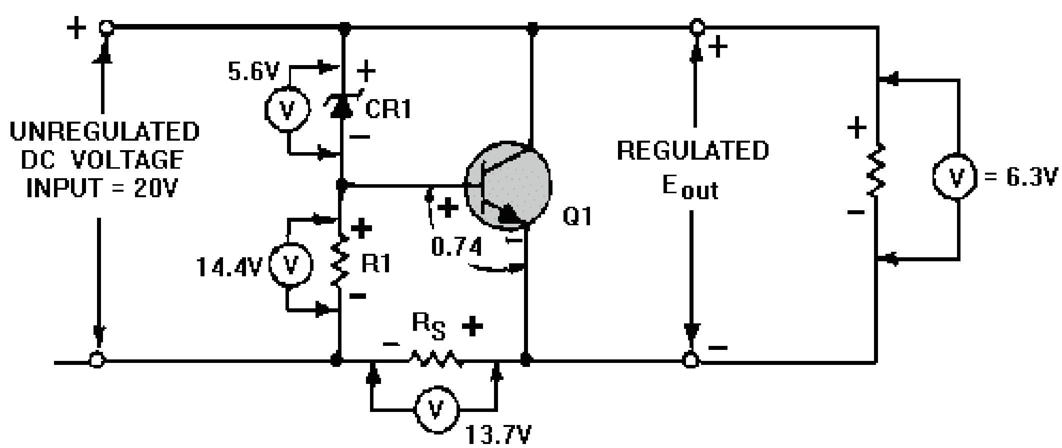


Figure 4-38.—Shunt voltage regulator (with voltages).

Now, refer to view A of figure 4-39. This figure shows the schematic diagram of the same shunt voltage regulator as that shown in figure 4-38 with an increased input voltage of 20.1 volts. This increases the forward bias on Q1 to 0.8 volt. Recall that the voltage drop across CR1 remains constant at 5.6 volts. Since the output voltage is composed of the Zener voltage and the base-emitter voltage, the output voltage momentarily increases to 6.4 volts. At this time, the increase in the forward bias of Q1 lowers the resistance of the transistor allowing more current to flow through it. Since this current must also pass through R_S, there is also an increase in the voltage drop across this resistor. The voltage drop across R_S is now 13.8 volts and therefore the output voltage is reduced to 6.3 volts. Remember, this change takes place in a fraction of a second.

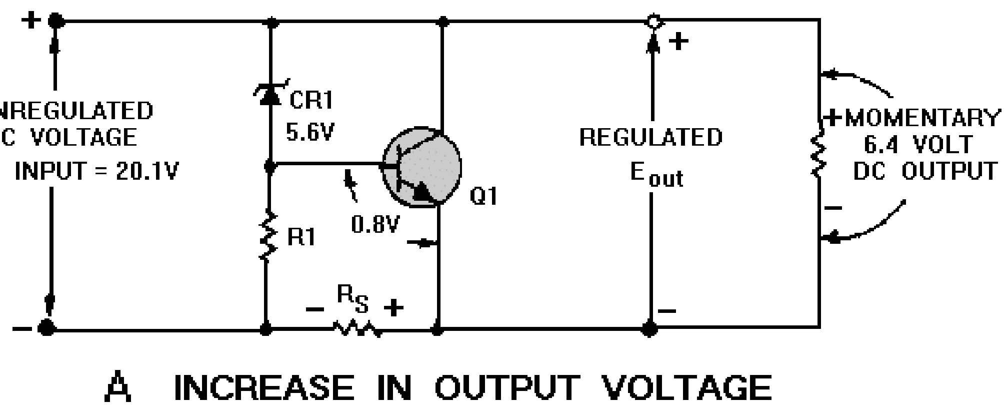


Figure 4-39A.—Shunt voltage regulator. INCREASE IN OUTPUT VOLTAGE

Study the schematic shown in view B. Although this schematic is identical to the other shunt voltage schematics previously illustrated and discussed, the output voltage is different. The load current has increased causing a momentary drop in voltage output to 6.2 volts. Recall that the circuit was designed to ensure a constant output voltage of 6.3 volts. Since the output voltage is less than that required, changes occur in the regulator to restore the output to 6.3 volts. Because of the 0.1 volt drop in the output voltage, the forward bias of Q1 is now 0.6 volt. This decrease in the forward bias increases the resistance of the transistor, thereby reducing the current flow through Q1 by the same amount that the load current increased. The current flow through R_S returns to its normal value and restores the output voltage to 6.3 volts.

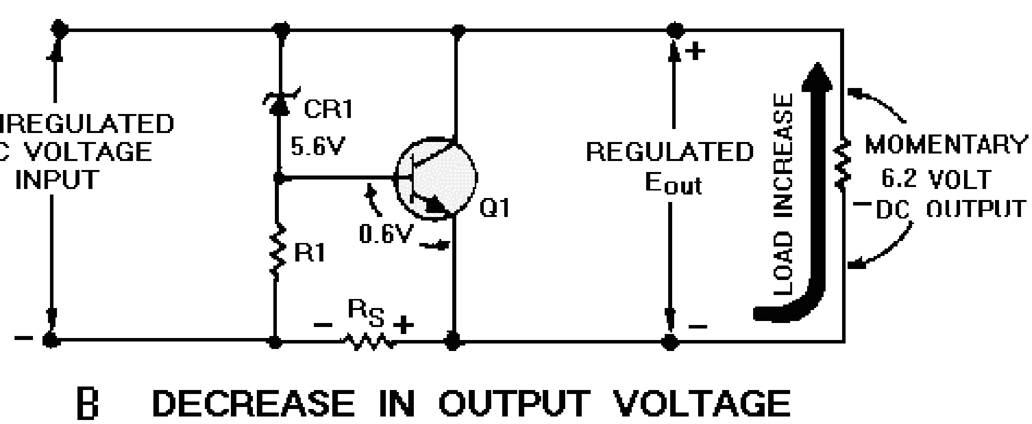


Figure 4-39B.—Shunt voltage regulator. DECREASE IN OUTPUT VOLTAGE

Q33. In figure 4-37, the voltage drop across R_S and R1 determines the amount of base-emitter ____ for Q1.

Q34. In figure 4-39, view A, when there is an increase in the input voltage, the forward bias of Q1 increases/decreases (which one).

Q35. In view B of figure 4-39, when the load current increases and the output voltage momentarily drops, the resistance of Q1 increase/decreases (which one) to compensate.

Current Regulators

You should now know how voltage regulators work to provide constant output voltages. In some circuits it may be necessary to regulate the current output. The circuitry which provides a constant current output is called a constant current regulator or just CURRENT REGULATOR. The schematic shown in figure 4-40 is a simplified schematic for a current regulator. The variable resistor shown on the schematic is used to illustrate the concept of current regulation. You should know from your study of voltage regulators that a variable resistor does not respond quickly enough to compensate for the changes. Notice that an ammeter has been included in this circuit to indicate that the circuit shown is that of a current regulator. When the circuit functions properly, the current reading of the ammeter remains constant. In this case the variable resistor (R_V) compensates for changes in the load or dc input voltage. Adequate current regulation results in the loss of voltage regulation. Studying the schematic shown, you should recall that any increase in load resistance causes a drop in current. To maintain a constant current flow, the resistance of R_V must be reduced whenever the load resistance increases. This causes the total resistance to remain constant. An increase in the input voltage must be compensated for by an increase in the resistance of R_V, thereby maintaining a constant current flow. The operation of a current regulator is similar to that of a voltage regulator. The basic difference is that one regulates current and the other regulates voltage.

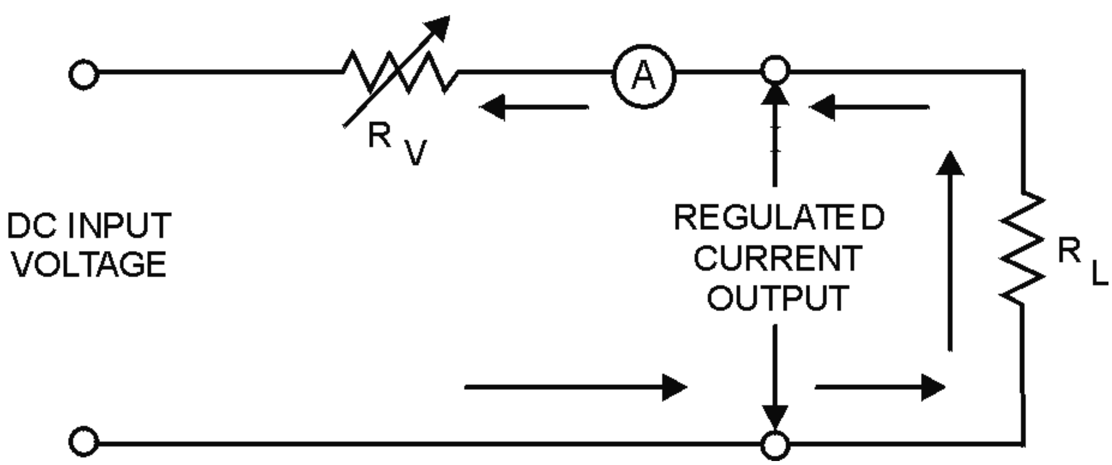


Figure 4-40.—Current regulator (simplified).

Since use of a variable resistor is not a practical way to control current fluctuation or variation, a transistor and a Zener diode, together with necessary resistors, are used. Recall that the Zener diode provides a constant reference voltage. The schematic shown in figure 4-41 is that of a current regulator circuit. Except for the addition of R1, the circuit shown in the figure is similar to that of a series voltage regulator. The resistor is connected in series with the load and senses any current changes in the load. Notice the voltage drop across R1 and the negative voltage polarity applied to the emitter of Q1. The voltage polarity is a result of current flowing through R1, and this negative voltage opposes the forward bias for Q1. However, since the regulated voltage across CR1 has an opposite polarity, the actual bias of the transistor is the difference between the two voltages. You should see that the purpose of R2 is to function as a current-limiting resistor for the Zener diode.

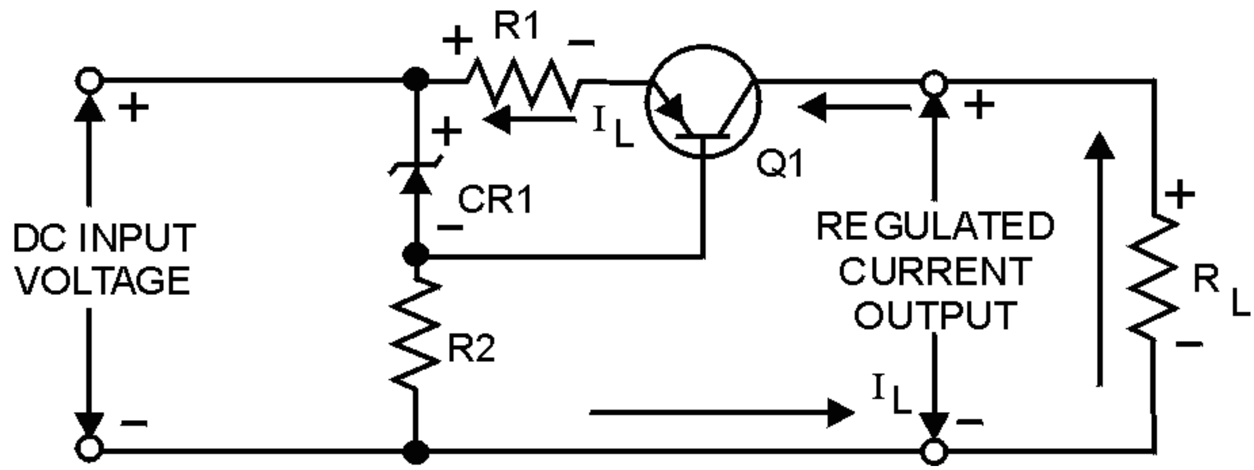


Figure 4-41.—Current regulator.

The purpose of a current regulator is to provide a constant current regardless of changes in the input voltage or load current. The schematic shown in figure 4-42 is that of a circuit designed to provide a constant current of 400 milliamperes. Voltmeters are shown in the schematic to emphasize the voltage drops across specific components. These voltages will help you understand how the current regulator operates. The voltage drop across the base-emitter junction of Q1 is 0.6 volt. This voltage is the difference between the Zener voltage and the voltage drop across R1. The 0.6-volt forward bias of Q1 permits proper operation of the transistor. The output voltage across R_L is 6 volts as shown by the voltmeter. With a regulated current output of 400 milliamperes, the transistor resistance (R_{Q1}) is 9 ohms. This can be proved by using Ohm's law and the values shown on the schematic. In this case, current (I) is equal to the voltage drop (E) divided by the resistance (R). Therefore: 12 volts divided by 30 ohms equals 0.4 ampere, or 400 milliamperes.

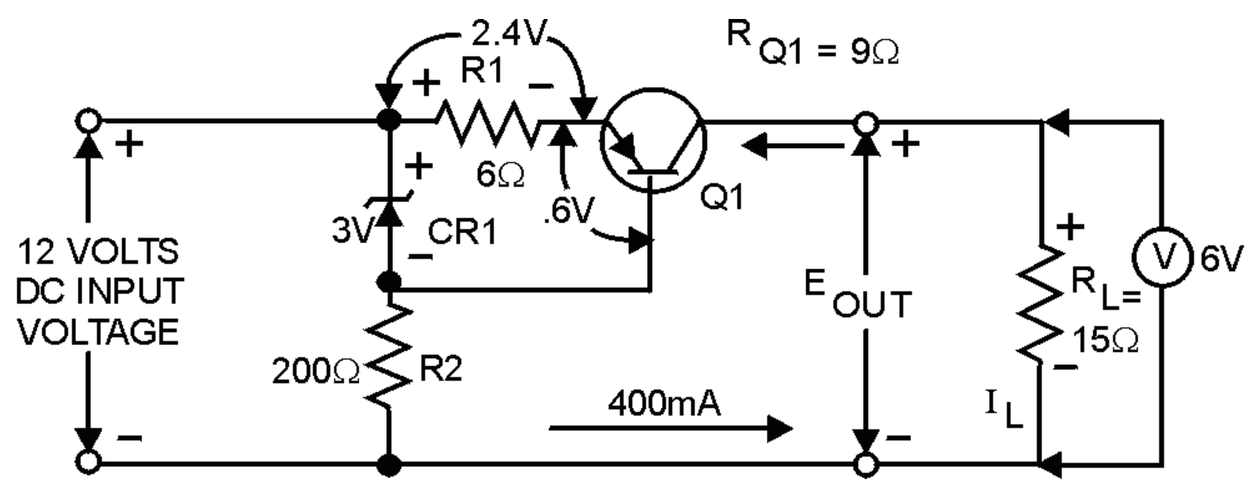


Figure 4-42.—Current regulator (with circuit values).

Since you are familiar with the basic current regulating circuitry, let's examine in detail how the various components work to maintain the constant 400-milliampere output. Refer to the schematic shown in figure 4-43. Remember a decrease in load resistance causes a corresponding increase in current flow. In the example shown, the load resistance R_L has dropped from 15 ohms to 10 ohms. This results in a larger voltage drop across R1 because of the increased current flow. The voltage drop has increased from 2.4 volts to 2.5 volts. Of course, the voltage drop across CR1 remains constant at 9 volts due to its regulating ability. Because of the increased voltage drop across R1, the forward bias on Q1 is now 0.5 volt. Since the forward bias of Q1 has decreased, the resistance of the transistor increases from 9 ohms to 14 ohms. Notice that the 5 ohm increase in resistance across the transistor corresponds to the 5 ohm decrease in the load resistance. Thus, the total resistance around the outside loop of the circuit remains constant. Since the circuit is a current regulator, you know that output voltages will vary as the regulator maintains a constant current output. In the figure, the voltage output is reduced to 4 volts, which is computed by multiplying current (I) times resistance (R) (400 mA × 10 ohms = 4 volts).

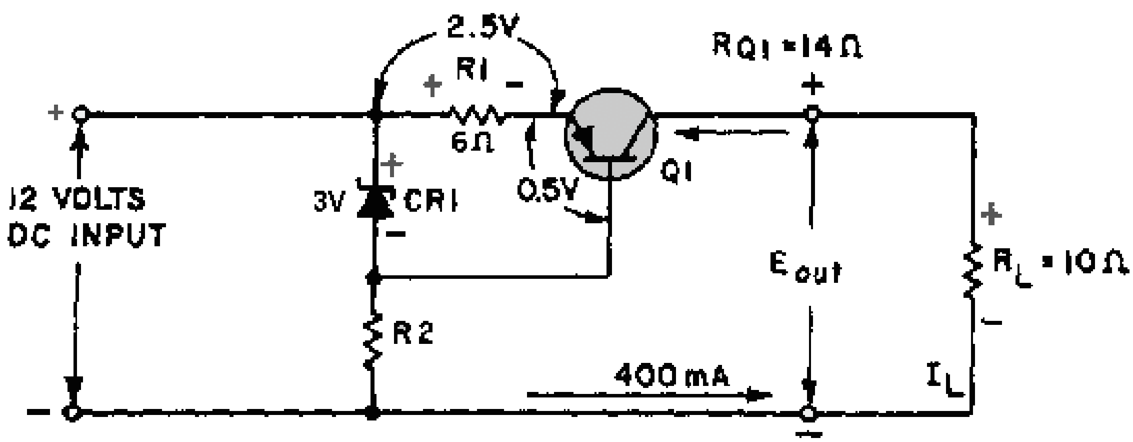


Figure 4-43.—Current regulator (with a decrease in R_L).

Q36. *In figure 4-40, when there is an increase in the load resistance (R_L), the resistance of R_V <u>increases/decreases</u> (which one) to compensate for the change.*

Q37. *In figure 4-43 any decrease in the base-emitter forward bias across Q1 results in <u>an increase/a decrease</u> (which one) in the resistance of the transistor.*

VOLTAGE MULTIPLIERS

You may already know how a transformer functions to increase or decrease voltages. You may also have learned that a transformer secondary may provide one or several ac voltage outputs which may be greater or less than the input voltage. When voltages are stepped up, current is decreased; when voltages are stepped down, current is increased.

Another method for increasing voltages is known as voltage multiplication. VOLTAGE MULTIPLIERS are used primarily to develop high voltages where low current is required. The most common application of the high voltage outputs of voltage multipliers is the anode of cathode-ray tubes (CRT), which are used for radar scope presentations, oscilloscope presentations, or TV picture tubes. The dc output of the voltage multiplier ranges from 1000 volts to 30,000 volts. The actual voltage depends upon the size of the CRT and its equipment application.

Voltage multipliers may also be used as primary power supplies where a 177 volt-ac input is rectified to pulsating dc. This dc output voltage may be increased (through use of a voltage multiplier) to as much as 1000 volts dc. This voltage is generally used as the plate or screen grid voltage for electron tubes.

If you have studied transformers, you may have learned that when voltage is stepped up, the output current decreases. This is also true of voltage multipliers. Although the measured output voltage of a voltage multiplier may be several times greater than the input voltage, once a load is connected the value of the output voltage decreases. Also any small fluctuation of load impedance causes a large fluctuation in the output voltage of the multiplier. For this reason, voltage multipliers are used only in special applications where the load is constant and has a high impedance or where input voltage stability is not critical.

Voltage multipliers may be classified as voltage doublers, triplers, or quadruplers. The classification depends on the ratio of the output voltage to the input voltage. For example, a voltage multiplier that increases the peak input voltage twice is called a voltage doubler. Voltage multipliers increase voltages through the use of series-aiding voltage sources. This can be compared to the connection of dry cells (batteries) in series.

The figures used in the explanation of voltage multipliers show a transformer input, even though for some applications a transformer is not necessary. The input could be directly from the power source or line voltage. This, of course, does not isolate the equipment from the line and creates a potentially hazardous condition. Most military equipments use transformers to minimize this hazard.

Figure 4-44 shows the schematic for a half-wave voltage doubler. Notice the similarities between this schematic and those of half-wave voltage rectifiers. In fact, the doubler shown is made up of two half-wave voltage rectifiers. C1 and CR1 make up one half-wave rectifier, and C2 and CR2 make up the other. The schematic of the first half-wave rectifier is indicated by the dark lines in view A of figure 4-45. The dotted lines and associated components represent the other half-wave rectifier and load resistor.

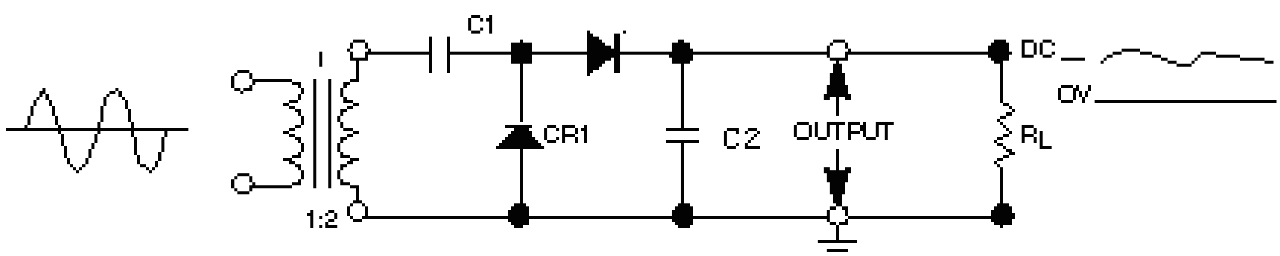


Figure 4-44.—Half-wave voltage doubler.

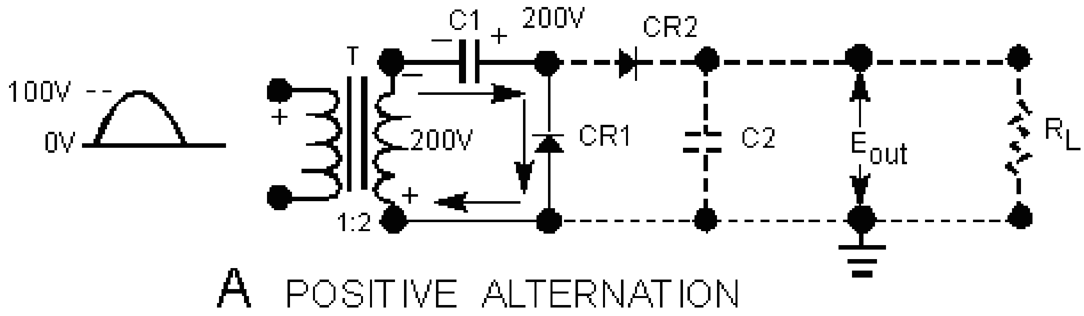


Figure 4-45A.—Rectifier action of CR1 and CR2. POSITIVE ALTERNATION

Notice that C1 and CR1 work exactly like a half-wave rectifier. During the positive alternation of the input cycle (view A), the polarity across the secondary winding of the transformer is as shown. Note that the top of the secondary is negative. At this time CR1 is forward biased (cathode negative in respect to the anode). This forward bias causes CR1 to function like a closed switch and allows current to follow the path indicated by the arrows. At this time, C1 charges to the peak value of the input voltage, or 200 volts, with the polarity shown.

During the period when the input cycle is negative, as shown in view B, the polarity across the secondary of the transformer is reversed. Note specifically that the top of the secondary winding is now positive. This condition now forward biases CR2 and reverse biases CR1. A series circuit now exists consisting of C1, CR2, C2, and the secondary of the transformer. The current flow is indicated by the arrows. The secondary voltage of the transformer now aids the voltage on C1. This results in a pulsating dc voltage of 400 volts, as shown by the waveform. The effect of series aiding is comparable to the connection of two 200-volt batteries in series. As shown in figure 4-46, C2 charges to the sum of these voltages, or 400 volts.

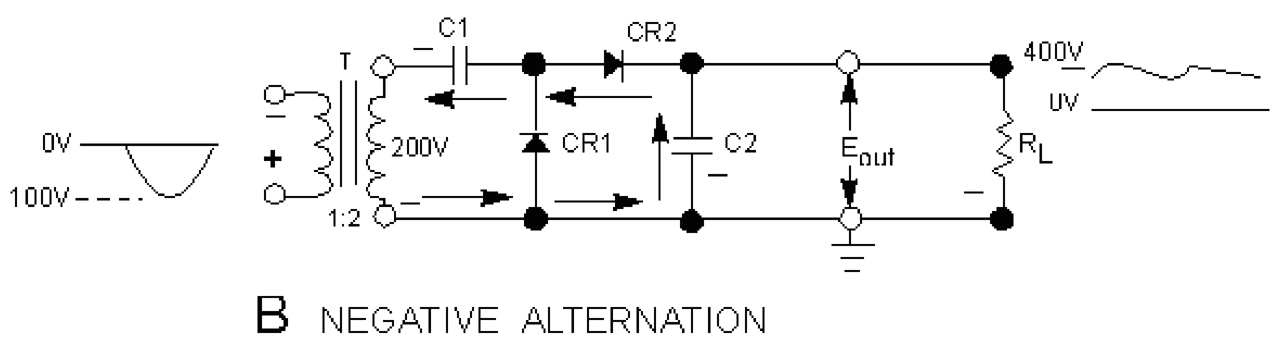


Figure 4-45B.—Rectifier action of CR1 and CR2. NEGATIVE ALTERNATION

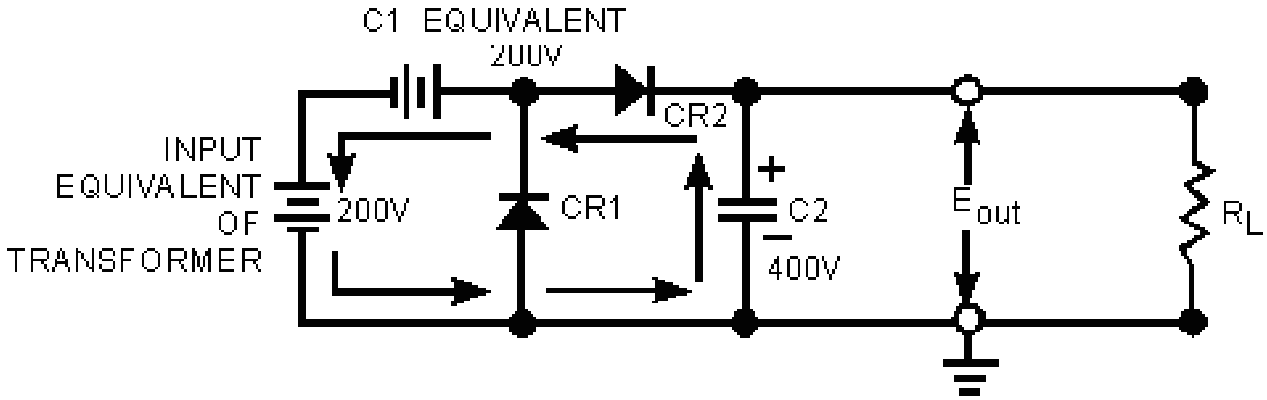


Figure 4-46.—Series-aiding sources.

The schematic shown in figure 4-47 is an illustration of a half-wave voltage tripler. When you compare figures 4-46 and 4-47, you should see that the circuitry is identical except for the additional parts, components, and circuitry shown by the dotted lines. (CR3, C3, and R2 make up the additional circuitry.) By themselves, CR3, C3, and R2 make up a half-wave rectifier. Of course, if you remove the added circuitry, you will once again have a half-wave voltage doubler.

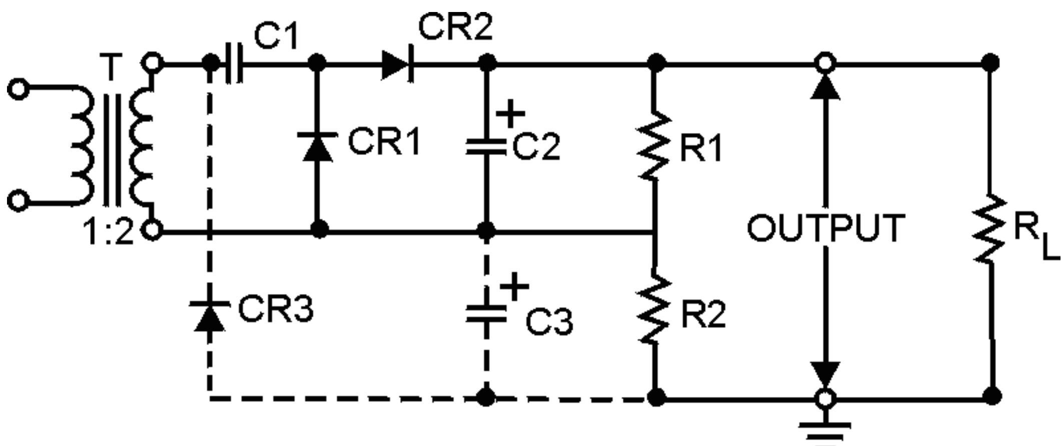


Figure 4-47.—Half-wave voltage tripler.

View A of figure 4-48 shows the schematic for the voltage tripler. Notice that CR3 is forward biased and functions like a closed switch. This allows C3 to charge to a peak voltage of 200 volts at the same time C1 is also charging to 200 volts.

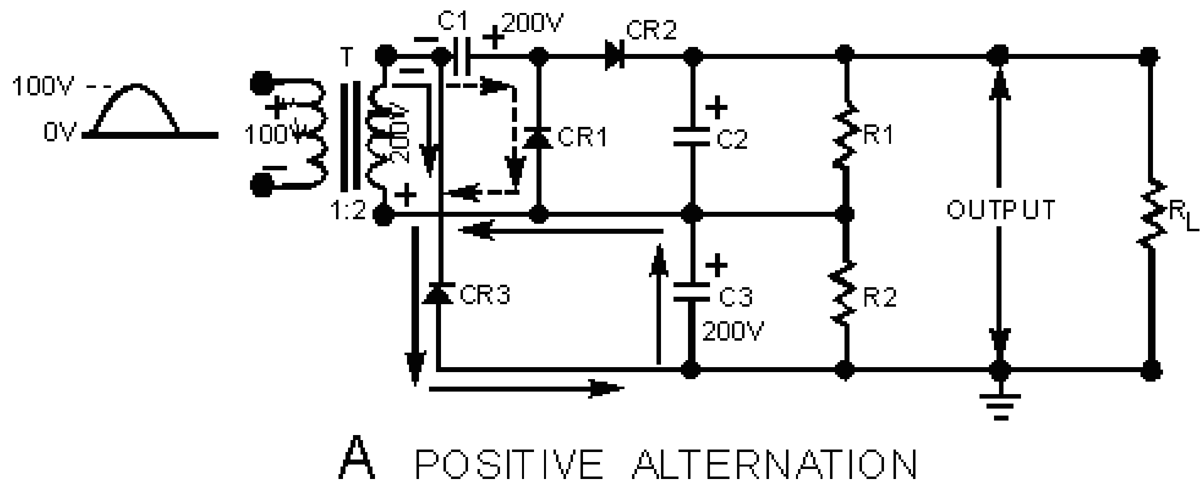


Figure 4-48A.—Voltage tripler. POSITIVE ALTERNATION

The other half of the input cycle is shown in view B. C2 is charged to twice the input voltage, or 400 volts, as a result of the voltage-doubling action of the transformer and C1. At this time, C2 and C3 are used as series-aiding devices, and the output voltage increases to the sum of their respective voltages, or 600 volts. R1 and R2 are proportional according to the voltages across C2 and C3. In this case, there is a 2 to 1 ratio.

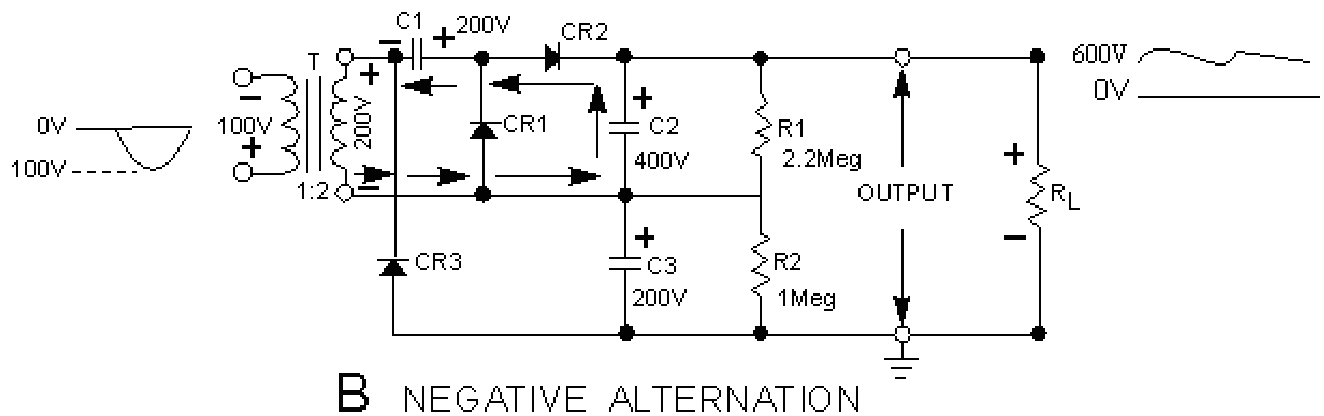


Figure 4-48B.—Voltage tripler. NEGATIVE ALTERNATION

The circuit shown in figure 4-49 is that of a full-wave voltage doubler. The main advantage of a full-wave doubler over a half-wave doubler is better voltage regulation, as a result of reduction in the output ripple amplitude and an increase in the ripple frequency. The circuit is, in fact, two half-wave rectifiers. These rectifiers function as series-aiding devices except in a slightly different way. During the alternation when the secondary of the transformer is positive at the top, C1 charges to 200 volts through CR1. Then, when the transformer secondary is negative at the top, C2 charges to 200 volts through CR2. R1 and R2 are equal value, balancing resistors that stabilize the charges of the two capacitors. Resistive load R_L is connected across C1 and C2 so that R_L receives the total charge of both capacitors. The output voltage is +400 volts when measured at the top of R_L, or point "A" with respect to point "B." If the output is measured at the bottom of R_L, it is –400 volts. Either way, the output is twice the peak value of the ac secondary voltage. As you can imagine, the possibilities for voltage multiplication are extensive.

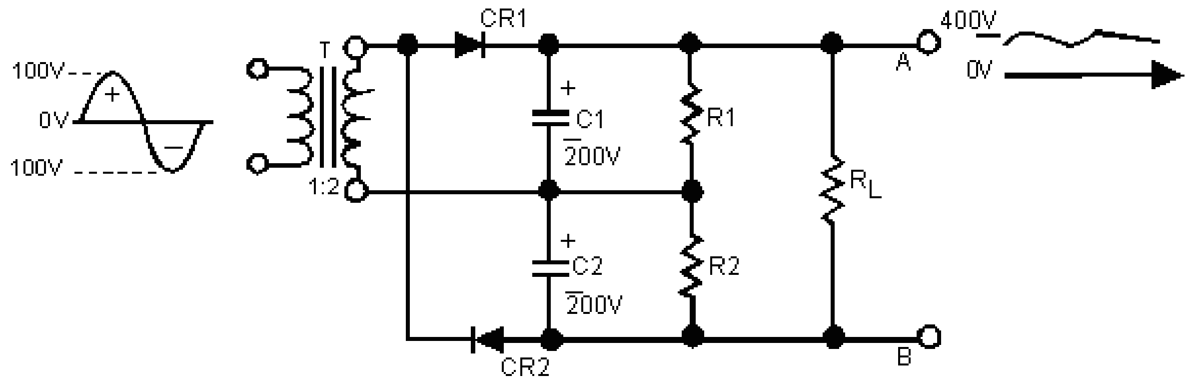


Figure 4-49.—Full-wave voltage doubler.

Q38. A half-wave voltage doubler is made up of how many half-wave rectifiers?

Q39. If a half-wave rectifier is added to a half-wave voltage doubler, the resulting circuit is a voltage ____.

Q40. In a full-wave voltage doubler, are the capacitors connected in series or in parallel with the output load?

Short Circuit Protection

The main disadvantage of a series regulator is that the pass transistor is in series with the load. If a short develops in the load, a large amount of current will flow in the regulator circuit. The pass transistor can be damaged by this excessive current flow. You could place a fuse in the circuit, but in many cases, the transistor will be damaged before the fuse blows. The best way to protect this circuit is to limit the current automatically to a safe value. A series regulator with a current-limiting circuit is shown in figure 4-50. You should recall that in order for a silicon NPN transistor to conduct, the base must be between 0.6 volt to 0.7 volt more positive than the emitter. Resistor R4 will develop a voltage drop of 0.6 volt when the load current reaches 600 milliamperes. This is illustrated using Ohm's law:

$$I = \frac{E}{R} = \frac{0.6\ volt}{1\ ohm} = .6 \text{ ampere or } 600 \text{ milliampere}$$

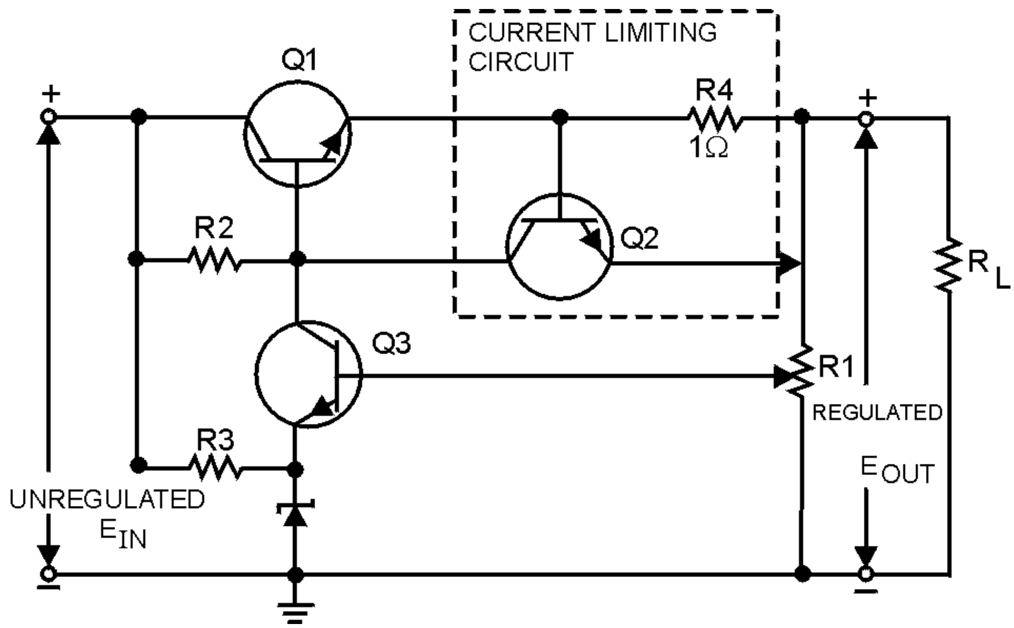


Figure 4-50.—Series regulator with current limiting.

When load current is below 600 milliamperes, the base-to-emitter voltage on Q2 is not high enough to allow Q2 to conduct. With Q2 cut off, the circuit acts like a series regulator.

When the load current increases above 600 milliamperes, the voltage drop across R4 increases to more than 0.6 volt. This causes Q2 to conduct through resistor R2, thereby decreasing the voltage on the base of pass transistor Q1. This action causes Q1 to conduct less. Therefore, the current cannot increase above 600 to 700 milliamperes.

By increasing the value of R4, you can limit the current to almost any value. For example, a 100-ohm resistor develops a voltage drop of 0.6 volt at 6 milliamperes of current. You may encounter current-limiting circuits that are more sophisticated, but the theory of operation is always the same. If you understand this circuit, you should have no problem with the others.

TROUBLESHOOTING POWER SUPPLIES

Whenever you are working with electricity, the proper use of safety precautions is of the utmost importance to remember. In the front of all electronic technical manuals, you will always find a section on safety precautions. Also posted on each piece of equipment should be a sign listing the specific precautions for that equipment. One area that is sometimes overlooked, and is a hazard especially on board ship, is the method in which equipment is grounded. By grounding the return side of the power transformer to the metal chassis, the load being supplied by the power supply can be wired directly to the metal chassis. Thereby the necessity of wiring directly to the return side of the transformer is eliminated. This method saves wire and reduces the cost of building the equipment, and while it solves one of the problems of the manufacturer, it creates a problem for you, the technician. Unless the chassis is physically grounded to the ship's ground (the hull), the chassis can be charged (or can float) several hundred volts above ship's ground. If you come in contact with the metal chassis at the same time you are in contact with the ship's hull, the current from the chassis can use your body as a low resistance path back to the ship's ac generators. At best this can be an unpleasant experience; at worst it can be fatal. For this reason Navy electronic equipment is always grounded to the ship's hull, and approved rubber mats are required in all spaces where electronic equipment is present. Therefore, before starting to work on any electronic or electrical equipment, ALWAYS ENSURE THAT THE EQUIPMENT AND ANY TEST EQUIPMENT YOU ARE USING IS PROPERLY GROUNDED AND THAT THE RUBBER MAT YOU ARE STANDING ON IS IN GOOD CONDITION. As long as you follow these simple rules, you should be able to avoid the possibility of becoming an electrical conductor.

TESTING

There are two widely used checks in testing electronic equipment, VISUAL and SIGNAL TRACING. The importance of the visual check should not be underestimated because many technicians find defects right away simply by looking for them. A visual check does not take long. In fact, you should be able to see the problem readily if it is the type of problem that can be seen. You should learn the following procedure. You could find yourself using it quite often. This procedure is not only for power supplies but also for any type of electronic equipment you may be troubleshooting. (Because diode and transistor testing was covered in chapter 1 and 2 of this module, it will not be discussed at this time. If you have problems in this area, refer to chapter 1 for diodes or chapter 2 for transistors.)

1. BEFORE YOU ENERGIZE THE EQUIPMENT, LOOK FOR:

   a. SHORTS—Any terminal or connection that is close to the chassis or to any other terminal should be examined for the possibility of a short. A short in any part of the power supply can cause considerable damage. Look for and remove any stray drops of solder, bits of wire, nuts, or screws. It sometimes helps to shake the chassis and listen for any tell-tale rattles. Remember to correct any problem that may cause a short circuit; if it is not causing trouble now, it may cause problems in the future.

   b. DISCOLORED OR LEAKING TRANSFORMER—This is a sure sign that there is a short somewhere. Locate it. If the equipment has a fuse, find out why the fuse did not blow; too large a size may have been installed, or there may be a short across the fuse holder.

   c. LOOSE, BROKEN, OR CORRODED CONNECTION—Any connection that is not in good condition is a trouble spot. If it is not causing trouble now, it will probably cause problems in the future. Fix it.

   d. DAMAGED RESISTORS OR CAPACITORS—A resistor that is discolored or charred has been subjected to an overload. An electrolytic capacitor will show a whitish deposit at the seal around the terminals. Check for a short whenever you notice a damaged resistor or a damaged capacitor. If there is no short, the trouble may be that the power supply has been overloaded in some way. Make a note to replace the part after signal tracing. There is no sense in risking a new part until the trouble has been located.

2. ENERGIZE THE EQUIPMENT AND LOOK FOR:

   a. SMOKING PARTS—If any part smokes or if you hear any boiling or sputtering sounds, remove the power immediately. There is a short circuit somewhere that you have missed in your first inspection. Use any ohmmeter to check the part once again. Start in the neighborhood of the smoking part.

   b. SPARKING—Tap or shake the chassis. If you see or hear sparking, you have located a loose connection or a short. Check and repair.

If you locate and repair any of the defects listed under the visual check, make a note of what you find and what you do to correct it. It is quite probable you have found the trouble. However, a good technician takes nothing for granted. You must prove to yourself that the equipment is operating properly and that no other troubles exist.

If you find none of the defects listed under the visual check, go ahead with the signal tracing procedure. The trouble is probably of such a nature that it cannot be seen directly-it may only be seen using an oscilloscope.

Tracing the ac signal through the equipment is the most rapid and accurate method of locating a trouble that cannot be found by a visual check, and it also serves as check on any repairs you may have made. The idea is to trace the ac voltage from the transformer, to see it change to pulsating dc at the rectifier output, and then see the pulsations smoothed out by the filter. The point where the signal stops or becomes distorted is the place look for the trouble. If you have no dc output voltage, you should look for an open or a short in your signal tracing. If you have a low dc voltage, you should look for a defective part and keep your eyes open for the place where the signal becomes distorted.

Signal tracing is one method used to localize trouble in a circuit. This is done by observing the waveform at the input and output of each part of a circuit.

Let's review what each part of a good power supply does to a signal, as shown in figure 4-51. The ac voltage is brought in from the power line by means of the line cord. This voltage is connected to the primary of the transformer through the ON-OFF switch (S1). At the secondary winding of the transformer (points 1 and 2), the scope shows you a picture of the stepped-up voltage developed across each half of the secondary winding-the picture is that of a complete sine wave. Each of the two stepped-up voltages is connected between ground and one of the two anodes of the rectifier diodes. At the two rectifier anodes (points 4 and 5), there is still no change in the shape of the stepped-up voltage-the scope picture still shows a complete sine wave.

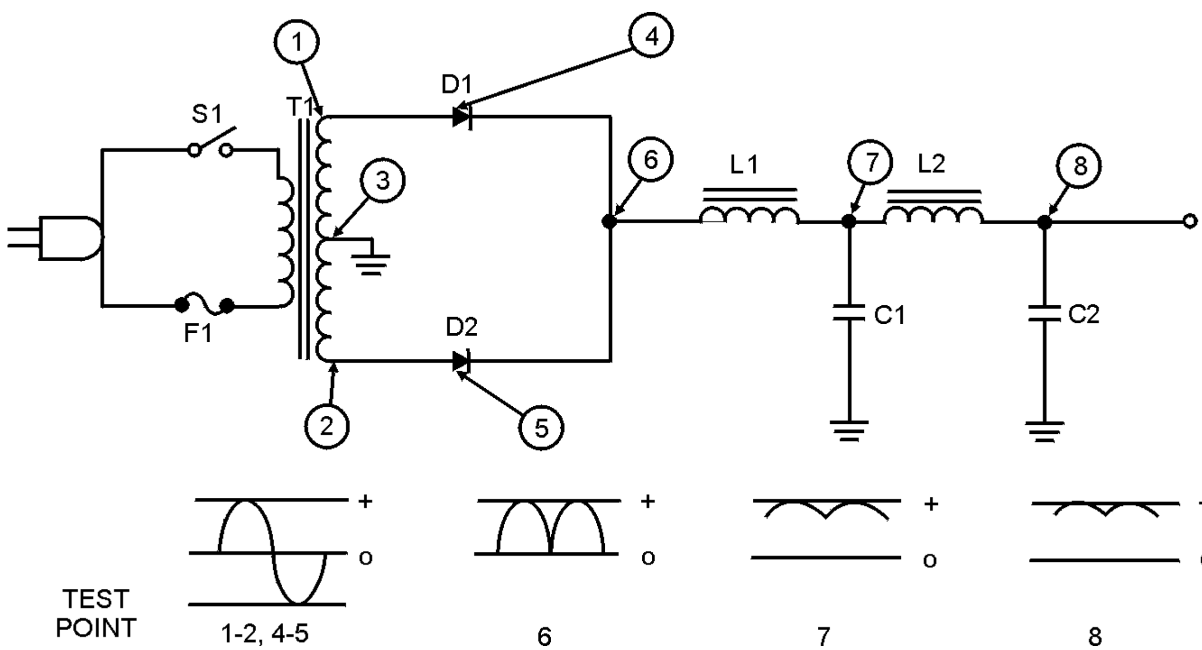


Figure 4-51.—Complete power supply (without regulator).

However, when you look at the scope pattern for point 6 (the voltage at the rectifier cathodes), you see the waveshape for pulsating direct current. This pulsating dc is fed through the first choke (L1) and filter capacitor (C1) which remove a large part of the ripple, or "hum," as shown by the waveform for point 7. Finally the dc voltage is fed through the second choke (L2) and filter capacitor (C2), which remove nearly all of the remaining ripple. (See the waveform for point 8, which shows almost no visible ripple.) You now have almost pure dc.

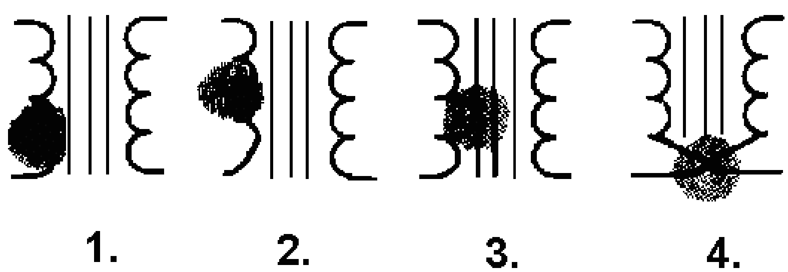
No matter what power supplies you use in the future, they all do the same thing—they change ac voltage into dc voltage.

Component Problems

The following paragraphs will give you an indication of troubles that occur with many different electronic circuit components.

TRANSFORMER AND CHOKE TROUBLES.—As you should know by now, the transformer and the choke are quite similar in construction. Likewise, the basic troubles that they may develop are comparable.

1. A winding can open.
2. Two or more turns of one winding can short together.
3. A winding can short to the casing, which is usually grounded.
4. Two windings (primary and secondary) can short together. This trouble is possible, of course, only in transformers.

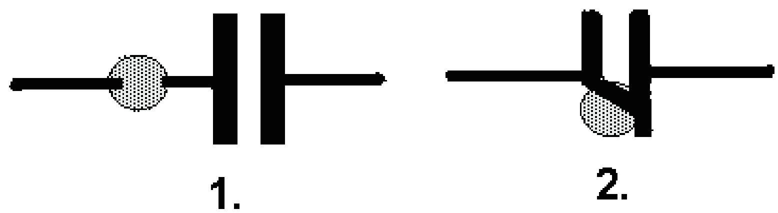


When you have decided which of these four possible troubles could be causing the symptoms, you have definite steps to take. If you surmise that there is an open winding, or windings shorted together or to ground, an ohmmeter continuity check will locate the trouble. If the turns of a winding are shorted together, you may not be able to detect a difference in winding resistance. Therefore, you need to connect a good transformer in the place of the old one and see if the symptoms are eliminated. Keep in mind that transformers are difficult to replace. Make absolutely sure that the trouble is not elsewhere in the circuit before you change the transformer.

Occasionally, the shorts will only appear when the operating voltages are applied to the transformer. In this case you might find the trouble with a megger-an instrument which applies a high voltage as it reads resistance.

CAPACITOR AND RESISTOR TROUBLES.—Just two things can happen to a capacitor:

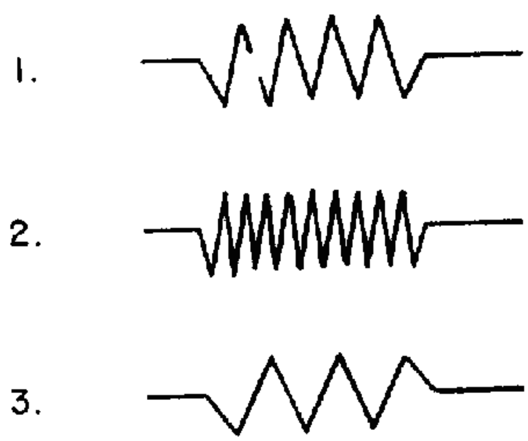
1. It may open up, removing the capacitor completely from the circuit.
2. It may develop an internal short circuit. This means that it begins to pass current as though it were a resistor or a direct short.



You may check a capacitor suspected of being open by disconnecting it from the circuit and checking it with a capacitor analyzer. You can check a capacitor suspected of being leaky with an ohmmeter; if it reads less than 500 kilohms, it is more than likely bad. However, capacitor troubles are difficult to find since they may appear intermittently or only under operating voltages. Therefore, the best check for a faulty capacitor is to replace it with one known to be good. If this restores proper operation, the fault was in the capacitor.

Resistor troubles are the simplest. However, like the others, they must be considered.

1. A resistor can open.
2. A resistor can increase in value.
3. A resistor can decrease in value.



You already know how to check possible resistor troubles. Just use an ohmmeter after making sure no parallel circuit is connected across the resistor you wish to measure. When you know a parallel circuit is connected across the resistor or when you are in doubt disconnect one end of the resistor before measuring it. The ohmmeter check will usually be adequate. However, never forget that occasionally intermittent troubles may develop in resistors as well as in any other electronic parts.

Although you may observe problems that have not been covered specifically in this chapter, you should have gained enough knowledge to localize and repair any problem that may occur.

Q41. What is the most important thing to remember when troubleshooting?

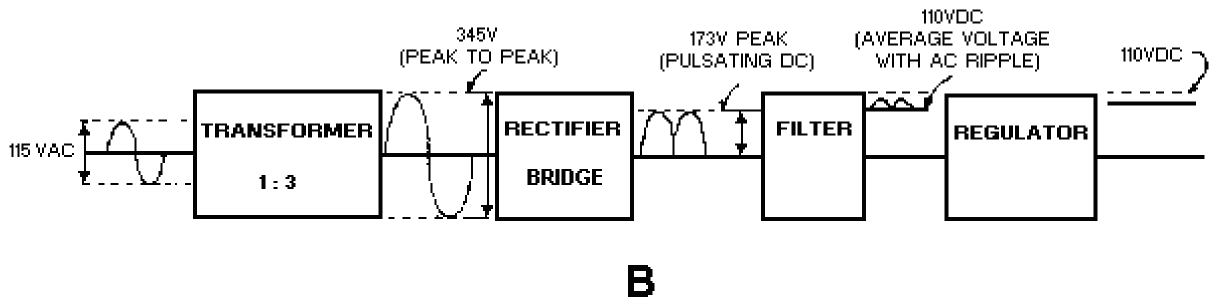
Q42. What is the main reason for grounding the return side of the transformer to the chassis?

Q43. What are two types of checks used in troubleshooting power supplies?

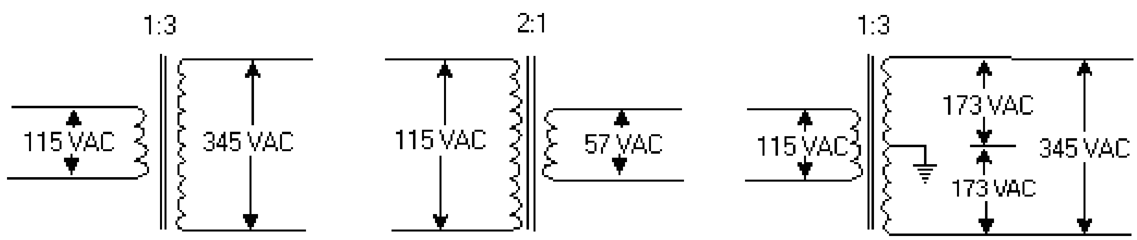
SUMMARY

This chapter has presented you with a basic description of the theory and operation of a basic power supply and its components. The following summary is provided to enhance your understanding of power supplies.

POWER SUPPLIES are electronic circuits designed to convert ac to dc at any desired level. Almost all power supplies are composed of four sections: transformer, rectifier, filter, and regulator.

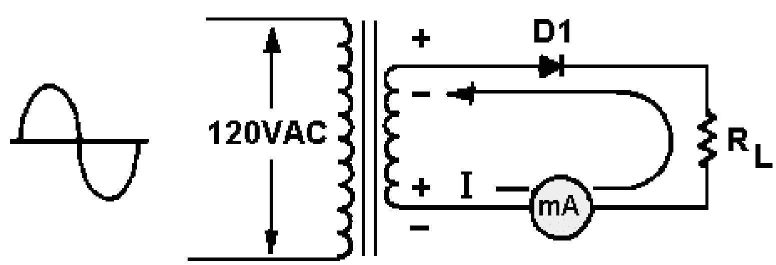


The **POWER TRANSFORMER** is the input transformer for the power supply.

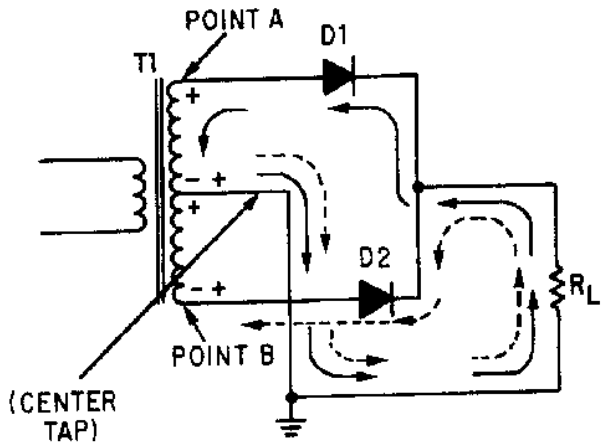


The **RECTIFIER** is the section of the power supply that contains the secondary windings of the power transformer and the rectifier circuit. The rectifier uses the ability of a diode to conduct during one half cycle of ac to convert ac to dc.

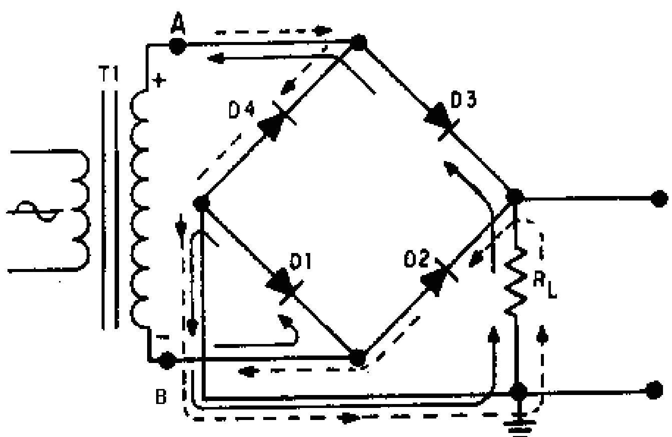
HALF-WAVE RECTIFIERS give an output on only one half cycle of the input ac. For this reason, the pulses of dc are separated by a period of one half cycle of zero potential voltage.



FULL-WAVE RECTIFIERS conduct on both halves of the input ac cycles. As a result, the dc pulses are not separated from each other. A characteristic of full-wave rectifiers is the use of a center-tapped, high-voltage secondary. Because of the center tap, the output of the rectifier is limited to one-half of the input voltage of the high-voltage secondary.

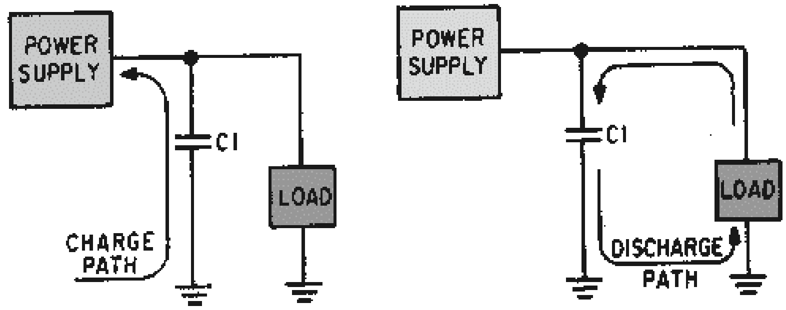


BRIDGE RECTIFIERS are full-wave rectifiers that do not use a center-tapped, high-voltage secondary. Because of this, their dc output voltage is equal to the input voltage from the high-voltage secondary of the power transformer. Bridge rectifiers use four diodes connected in a bridge network. Diodes conduct in diagonal pairs to give a full-wave pulsating dc output.

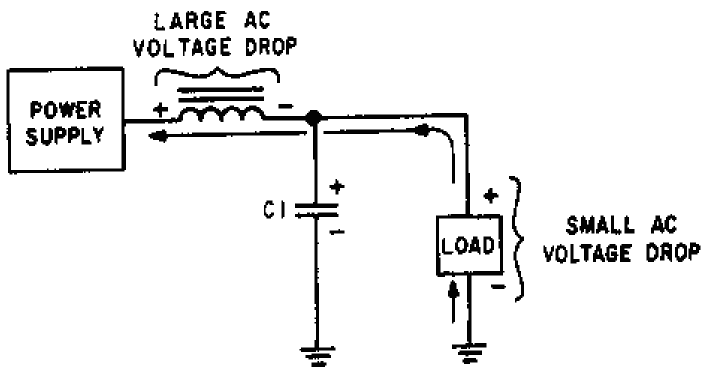


FILTER CIRCUITS are designed to smooth, or filter, the ripple voltage present on the pulsating dc output of the rectifier. This is done by an electrical device that has the ability to store energy and to release the stored energy.

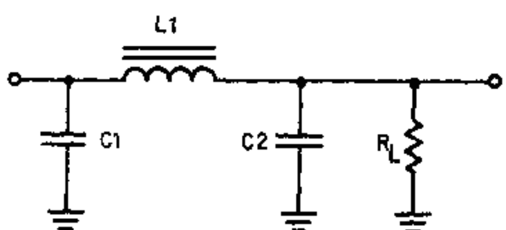
CAPACITANCE FILTERS are nothing more than large capacitors placed across the output of the rectifier section. Because of the large size of the capacitors, fast charge paths, and slow discharge paths, the capacitor will charge to average value, which will keep the pulsating dc output from reaching zero volts.

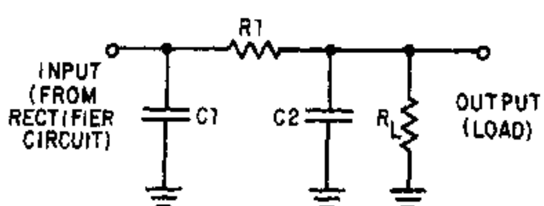


INDUCTOR FILTERS use an inductor called a choke to filter the pulsating dc input. Because of the impedance offered to circuit current, the output of the filter is at a lower amplitude than the input.



PI-TYPE FILTERS use both capacitive and inductive filters connected in a pi-type configuration. By combining filtering devices, the ability of the pi filter to remove ripple voltage is superior to that of either the capacitance or inductance filter.

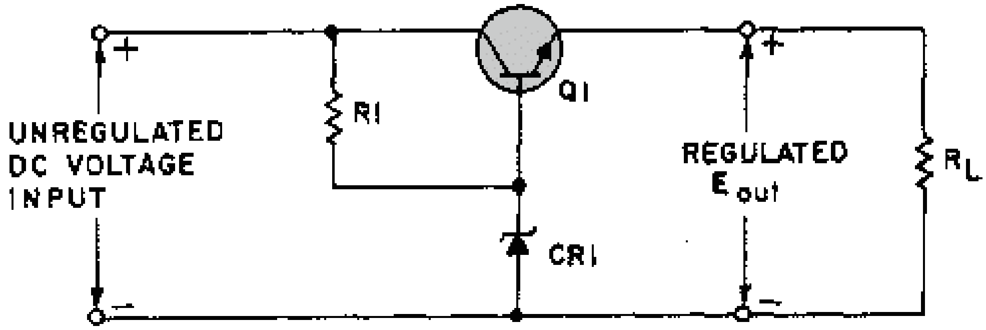




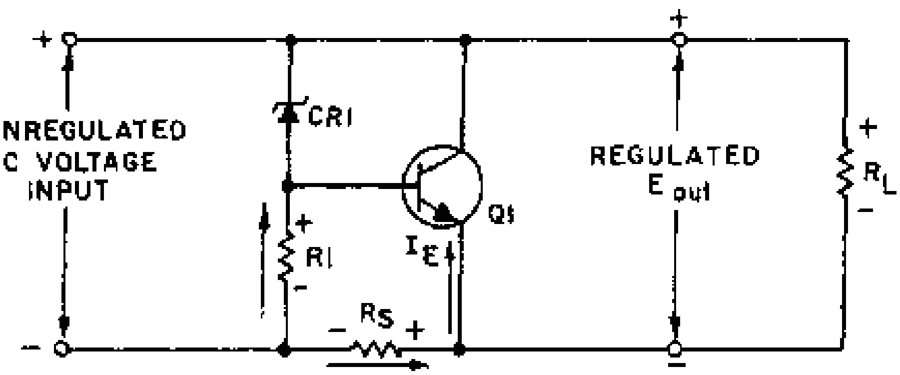
VOLTAGE REGULATORS are circuits designed to maintain the output of power supplies at a constant amplitude despite variations of the ac source voltage or changes of the resistance of the load.

This is done by creating a voltage divider of a resistive element in the regulator and the resistance of the load. Regulation is achieved by varying the resistance of the resistive element in the regulator.

A **SERIES REGULATOR** uses a variable resistance in series with the load. Regulation is achieved by varying this resistance either to increase or to decrease the voltage drop across the resistive element of the regulator. Characteristically, the resistance of the variable resistance moves in the same direction as the load. When the resistance of the load increases, the variable resistance of the regulator increases; when load resistance decreases, the variable resistance of the regulator decreases.



SHUNT REGULATORS use a variable resistance placed in parallel with the load. Regulation is achieved by keeping the resistance of the load constant. Characteristically the resistance of the shunt moves in the opposite direction of the resistance of the load.



The **CURRENT LIMITER** is a short-circuit protection device that automatically limits the current to a safe value. This is done when the current-limiting transistor senses an increase in load current. At this time the current-limiting transistor decreases the voltage on the base of the pass transistor in the regulator, causing a decrease in its conduction. Therefore, current cannot rise above a safe value.

TROUBLESHOOTING is a method of detecting and repairing problems in electronic equipment. Two methods commonly used are the **VISUAL CHECK** and **SIGNAL TRACING**. The visual check allows the technician to make a quick check of component problems, such as shorts, discolored or leaky transformers, loose or broken connections, damaged resistors or capacitors, smoking parts, or sparking. The signal tracing method is used when the technician cannot readily see the problem and needs to use test equipment. Component failure is also important in troubleshooting. In transformers and chokes, a winding can open, or two or more windings can short, either to themselves or to the case that is usually grounded. In a capacitor only two things can occur: either it can short and act as a resistor, or it can open, removing it from the circuit. A resistor can open, increase in value, or decrease in value.

ANSWERS TO QUESTIONS Q1. THROUGH Q43.

A1. *Transformer, rectifier, filter, regulator.*

A2. *To change ac to pulsating dc.*

A3. *To change pulsating dc to pure dc.*

A4. *To maintain a constant voltage to the load.*

A5. *The half-wave rectifier.*

A6. *15.9 volts.*

A7. *It isolates the chassis from the power line.*

A8. *The fact that the full-wave rectifier uses the full output, both half cycles, of the transformer.*

A9. *120 hertz.*

A10. *63.7 volts.*

A11. *Peak voltage is half that of the half-wave rectifier.*

A12. *The bridge rectifier can produce twice the voltage with the same size transformer.*

A13. *It will decrease. Capacitance is inversely proportional to:*

$$X_C \left(X_C = \frac{1}{2\pi fC}\right).$$

A14. *The capacitor filter.*

A15. *Parallel.*

A16. *At a high frequency.*

A17. *A filter circuit increases the average output voltage.*

A18. *Value of capacitance and load resistance.*

A19. *Good.*

A20. *Yes.*

A21. *The CEMF of the inductor.*

A22. *From 1 to 20 henries.*

A23. *Decrease.*

A24. *Expense.*

A25. *When ripple must be held at an absolute minimum.*

A26. *LC capacitor-input filter.*

A27. Cost and size of the inductor.

A28. Regulators.

A29. Variation.

A30. Series and shunt.

A31. An increase.

A32. In parallel.

A33. Bias.

A34. Increases.

A35. Increases.

A36. Decreases.

A37. An increase.

A38. Two.

A39. Trippler.

A40. In parallel.

A41. Safety precautions.

A42. To eliminate shock hazard.

A43. Visual and signal tracing.